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LASER VELOCIMETER APPLICATION TO OSCILLATORY LIQUID FLOWS

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SUMMARY

A laser velocimeter technique has been used to measure the mean velocity and the frequency characteristics of an oscillatory flow component generated with a rotating flapper in a liquid flow system at Reynolds numbers approximating 93,000. The velocity information was processed in the frequency domain using a tracker whose output (analog form) was used to determine the flow spectrum. This was accomplished with the use of an auto-correlator/Fourier transform analyzer and a spectrum averaging analyzer where induced flow oscillations up to 40 Hz were detected. Tests were conducted at a mean flow velocity of approximately 2 m/s. The experimental results show that the laser velocimeter can provide quantitative information such as liquid flow velocity and frequency spectrum with a possible application to cryogenic fluid flows. A proposed final system is discussed in the appendix.

INTRODUCTION

The spontaneously occurring longitudinal vibrations, nicknamed POGO, have been experienced in many liquid propellant rocket vehicles. The frequency and the intensity of these vibrations, which occur typically for 10 to 40 seconds, are in the order of 5 to 60 Hz and 17 to 34 g's, respectively. The structural vibrations can produce an intolerable environment to astronauts, equipment, and vehicle structure. In addition, it can cause adverse effects to the performance of the propulsion system (ref. 1).

In order to obtain a better understanding of the propellant fluid dynamics contributing to these oscillations through quantitative means, a technique for determining the mean velocity and the flow spectrum is needed. References 1 and 2 discuss the use of piezoelectric transducers for propagating ultrasonic waves in a moving fluid for determining the velocity. The velocity measurement is determined from the time or phase variations resulting from ultrasonic waves traveling across the flow from opposite points of a path inclined at some angle to the flow. These variations are inversely proportional to the square of the fluid sound velocity which is a function of temperature and pressure. Since the sound velocity for a given fluid is dependent on temperature and pressure, a simultaneous measure of the variations for waves propagating in the same direction (and opposite direction) of the flow and proper relative phasing of the transmitted waves can compensate for the effects of these parameters, thus allowing the velocity to be obtained completely

independent of the sound velocity in the fluid. There are two significant drawbacks in using the ultrasonic wave technique. They are stated as (1) the system suffers from signal dropout when gas bubbles contaminate the fluid sample region and (2) the long term reliability of the piezoelectric transducers operating in cryogenic fluids is uncertain.

With the current progress in laser velocimeter (LV), many types of fluid measurements have been made possible. The present work study was undertaken to investigate the feasibility of using laser velocimetry for measuring the velocity flow field and frequency characteristics of fluid flow having oscillatory structure. The results from this study could possibly serve as a basis for future experiments featuring dynamic cryogenic flows such as those related to the space shuttle program.

Fluid flow measurements have been made under controlled laboratory conditions. A brief description of the measurement principle (LV) and a discussion of the experimental results are presented.

SYMBOLS

f_D	= Doppler frequency, Hz
N_R	= Reynolds number
$R(\tau)$	= correlation function
S_f	= fringe spacing, meter
T	= period, seconds; integration time
V	= velocity, meters/sec
λ	= wavelength of laser light, meter
θ	= angle between intersecting laser beams, degrees
τ	= delay time
ψ	= phase angle
ω	= angular frequency
ω_d	= Doppler angular frequency

APPARATUS AND PROCEDURES

Laser Velocimetry Technique

Shown in figure 1 are two intersecting laser beams of wavelength λ with an included angle θ . At the point of intersection of the two beams, a stationary fringe pattern is formed, which is designated as the sample volume. The fringe pattern is a combination of alternating light and dark regions of equal spacing. The fringe spacing S_f , is given by

$$S_f = \frac{\lambda}{2 \sin \theta/2} \quad (1)$$

Particles suspended in a moving fluid, with a diameter less than the fringe spacing will cause light to be scattered, according to the Mie theory, with a resultant burst signal whose period, T , is equal to the inverse Doppler frequency shift of the incident laser radiation. The Doppler frequency, f_D , is linearly proportional to the velocity component of the particle normal to the fringe pattern. That is

$$f_D = \frac{V}{S_f} \quad (2)$$

where S_f is the fringe spacing.

Test Apparatus

The water flow system in figure 2 is a recirculating type unit that provides flow rates up to 2 m/s, depending on a manual controlled reservoir head level. There were overflow sections located at various levels that provided additional head-level control. The local Reynolds number was approximately 93,000. Axial velocity measurements within a 4.7-cm-diameter pipe were made approximately 5 meters downstream of the flow entrance section. A flapper used to produce known flow oscillations in the flow up to 60 Hz was located at the exit section. The rotational speed of the flapper was monitored electronically. Naturally occurring and seeded 1- μ m-diameter alumina particles in the flow were used as scattering centers.

The laser velocimeter shown in figure 3 was used to measure the velocities and velocity fluctuations in the pipe flow. The system which incorporates a 15-mw He-Ne laser ($\lambda = 632.8$ nm) was operated in the forward-scatter mode with a crossbeam angle of 11.6 degrees.

A schematic diagram of the signal processing electronics is shown in figure 4. The signal from the photodetector is processed by a frequency

tracker. This signal processor, with an operational range of 2 kHz to 30 MHz, converts the Doppler frequency into a proportional analog voltage. This unit has the capability of measuring velocity fluctuations of better than 100:1, thereby permitting velocity measurements in environments of very large turbulence intensity. The input signal was nearly continuous, i.e., the data rates were in the order of 10^5 samples per second. The output from the tracker was low-pass filtered to about 1 kHz and fed into a correlator-Fourier analyzer system and an averaging spectrum analyzer for determining the frequency characteristics of the velocity flow field. The experimental results were recorded on a film and by an x-y plotter.

Test Procedure

During each series of test, the mean velocity was measured and held constant by controlling the height of the water level in the reservoir tank. Next, a rotating flapper was used to interrupt the flow to create approximately sinusoidal oscillations ranging from 10 to 40 Hz, depending on the flapper speed. The frequency characteristics of the flow was measured using two processing techniques both operating from the Doppler signal processor analog output which is proportional to the detected flow velocity. The first method entails averaging individually measured spectra using a digital recursion process. The second method entails performing an autocorrelation of the output signal and Fourier transforming the results.

RESULTS AND DISCUSSION

The estimated autocorrelation function, $R(\tau)$, a representation of the similarity of a waveform and its replica as a function of a delay time (τ), can be expressed as

$$\hat{R}(\tau) = \frac{1}{T} \int_0^T f(t) f(t + \tau) dt \quad (3)$$

where T is the integration time, and τ is the delay.

For a continuous input signal in the form

$$f(t) = A \sin(\omega_0 t + \psi) \quad (4)$$

with a randomly varying phase ψ , the autocorrelation function is

$$R(\tau) = \frac{A^2}{2} \cos \omega_0 \tau \quad (5)$$

Taking the Fourier transform of the autocorrelation function, $\hat{R}(\tau)$, yields a one-sided power spectral density $|F(\omega)|^2$ of $f(t)$, i.e.,

$$F[R(\tau)] = \int_0^{\infty} \hat{R}(\tau) e^{-j\omega\tau} d\tau = |F(\omega)|^2 \quad (6)$$

where

$$F(\omega) = \frac{A^2}{2} [\delta(\omega - \omega_0)] \quad (7)$$

Shown in figures 5, 6, 7, and 8 are the autocorrelation function and the power spectral density for 10, 20, 30, and 40 Hz induced flow oscillations, respectively. In each of these spectrum plots the frequencies indicated were obtained from a position marker and digital display (a feature of the Fourier transform analyzer).

The data from the averaging spectrum analyzer is shown in figures 9, 10, and 11. The frequency spectrum of the overall flow without the flapper is shown in figure 9. The amplitude of the flow oscillation varied approximately inversely to the rotating flapper speed. As the oscillations were increased to about 40 Hz, it was difficult to distinguish the spectrum of the induced oscillations from the background turbulence. However, with longer averaging time (≈ 60 sec) the 40 Hz oscillations were detectable (see figs. 8 and 11).

In general the autocorrelation/Fourier transform method yields the better results. These findings were particularly evident at the higher induced frequencies. The fact that 40 Hz was the upper limit frequency attempted for these experiments does not imply that this is the system's maximum capability in distinguishing higher frequencies. The results were limited to 40 Hz because of the inherent features of the oscillatory flow system, i.e., the amplitude of the oscillations were coupled to the oscillatory frequency and varied nearly inversely proportional to it. In other words, at the higher frequencies (flapper speed) the amplitudes of the induced oscillations decreased to the background turbulence level where they became difficult to distinguish. However, in measurement situations where the amplitude and induced oscillations are uncoupled, higher frequencies could be detected using this measurement technique.

CONCLUSION

A laser velocimeter technique has been used to measure the mean velocity and the power spectrum of a liquid flow system, with Reynolds numbers in the

order of 93,000. The velocity information was processed in the frequency domain using a tracker whose output (analog form) was used to determine the flow frequency characteristics. This was accomplished with the use of an autocorrelator/Fourier transform analyzer and a spectrum averaging analyzer, where induced flow oscillations up to 40 Hz were detected. Tests were conducted at mean flow velocities in the order of 2 m/s. The experimental results show that the laser velocimeter can provide quantitative information such as flow velocity and frequency spectrum with possible transition to cryogenic flows. A proposed final system is discussed in the appendix.

REFERENCES

1. Pedersen, N. E.; Lynnworth, L. C.; and Carnevale, E. H.: Nonintrusive Dynamic Flowmeter. Final Report, NAS1-11756 and NASA CR-112313, June 1973.
2. Alaia, P. and Demarais, J. C.: Measurement of Rapidly Varying Hydraulic Flow Rates by Ultrasonic Waves. *Extrait de LaRecherche Aerospatiale*, no. 1972-2 (mars-avril), pp. 61-73, NASA TTF-14, 392.
3. Meyers, J. F. and Walsh, M. J.: Computer Simulation of a Fringe Type Laser Velocimeter. *Proceedings of Second International Workshop on Laser Velocimeter*, Vol. I, H. D. Thompson and W. H. Stevenson, eds., Purdue Univ., pp. 471-510, March 1974.

APPENDIX

Proposed Laser Velocimeter System J. M. Franke and L. R. Gartrell

A mini-laser velocimeter system is proposed as a final system. The components for the system are small and can be housed very compactly. The active devices are 100% solid state for better reliability and power consumption efficiency. The laser source characteristics are shown in Table 1A.

A computer program for theoretically evaluating laser velocimeters (ref. 3) was used to examine the signal and signal levels as a function of time at a fixed distance, 5.08 cm and fixed f-number, 2.54. The input parameters in the program are given in Table 1A. Results of an extension of this program are shown in figure 1A where the expected signal to noise is plotted as a function of f-number for a given particle size (0.5 - 5 micrometers).

The predicted signal-to-noise ratio as a function of bandwidth, laser power, and distance can be expressed as:

$$\text{SNR} = \text{SNR}_{\text{graph}} + 10 \log \left[\frac{KP}{(\text{BW}) d^2} \right] \quad (1A)$$

where $K = \text{constant} \left(50 \frac{\text{MHz cm}^2}{\text{mw}} \right)$

BW = bandwidth (MHz)

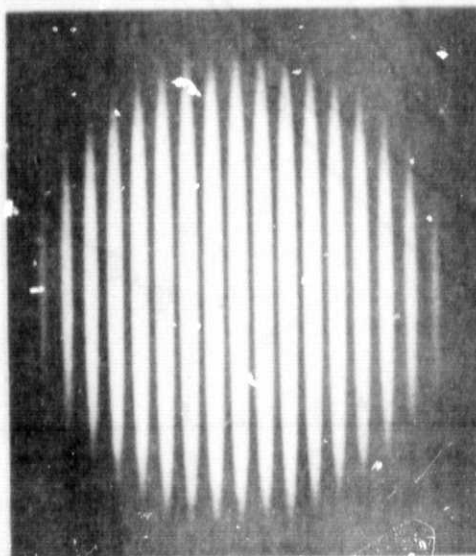
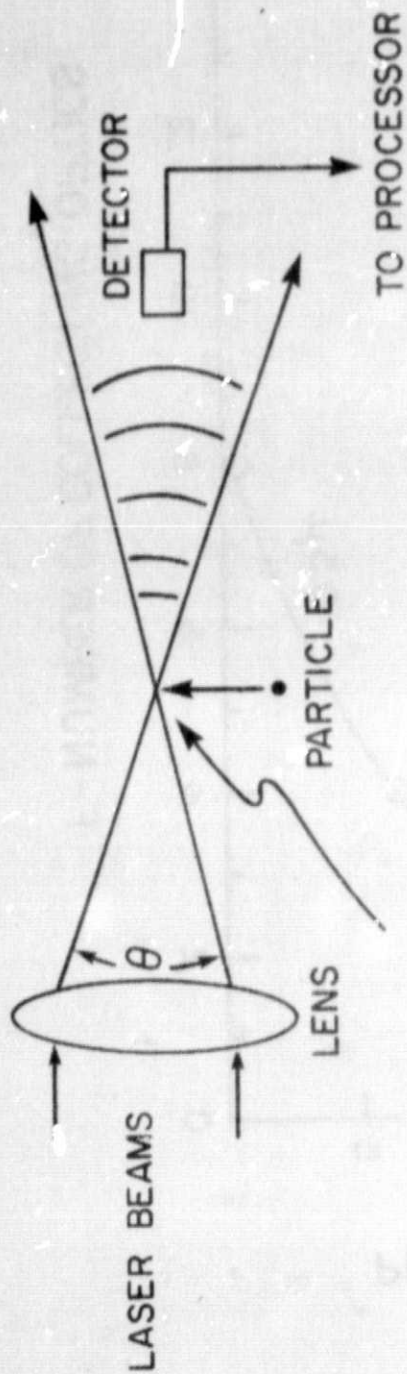
d = distance (cm)

P = laser power (mw)

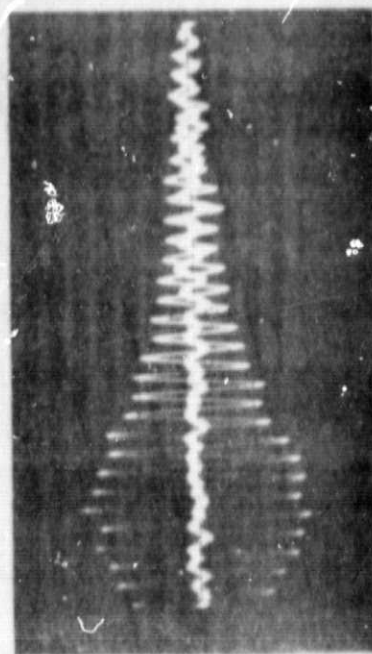
A prototype mini-LV system has been demonstrated in the laboratory where mean flow velocity in the circular pipe was measured. The system was operated in the forward-scatter mode, as shown in figure 2A. The proposed final system is shown in figure 3A.

TABLE 1A.- PROGRAM INPUT PARAMETERS

Laser wavelength	765.0 nm
Laser power	0.015 watt
Beam diameter	0.25 mm
Transmission coefficient	0.50
Input lens focal length	5.08 cm
Crossbeam angle	4.373°
Collecting lens diameter	Varied
Receiving coefficient	0.50
Electronic input impedance	50 ohms
Electronics bandwidth	29 MHz
Fringe spacing	10.0 micrometers
Beam waist	0.197 mm
Sample volume length	3.66 mm



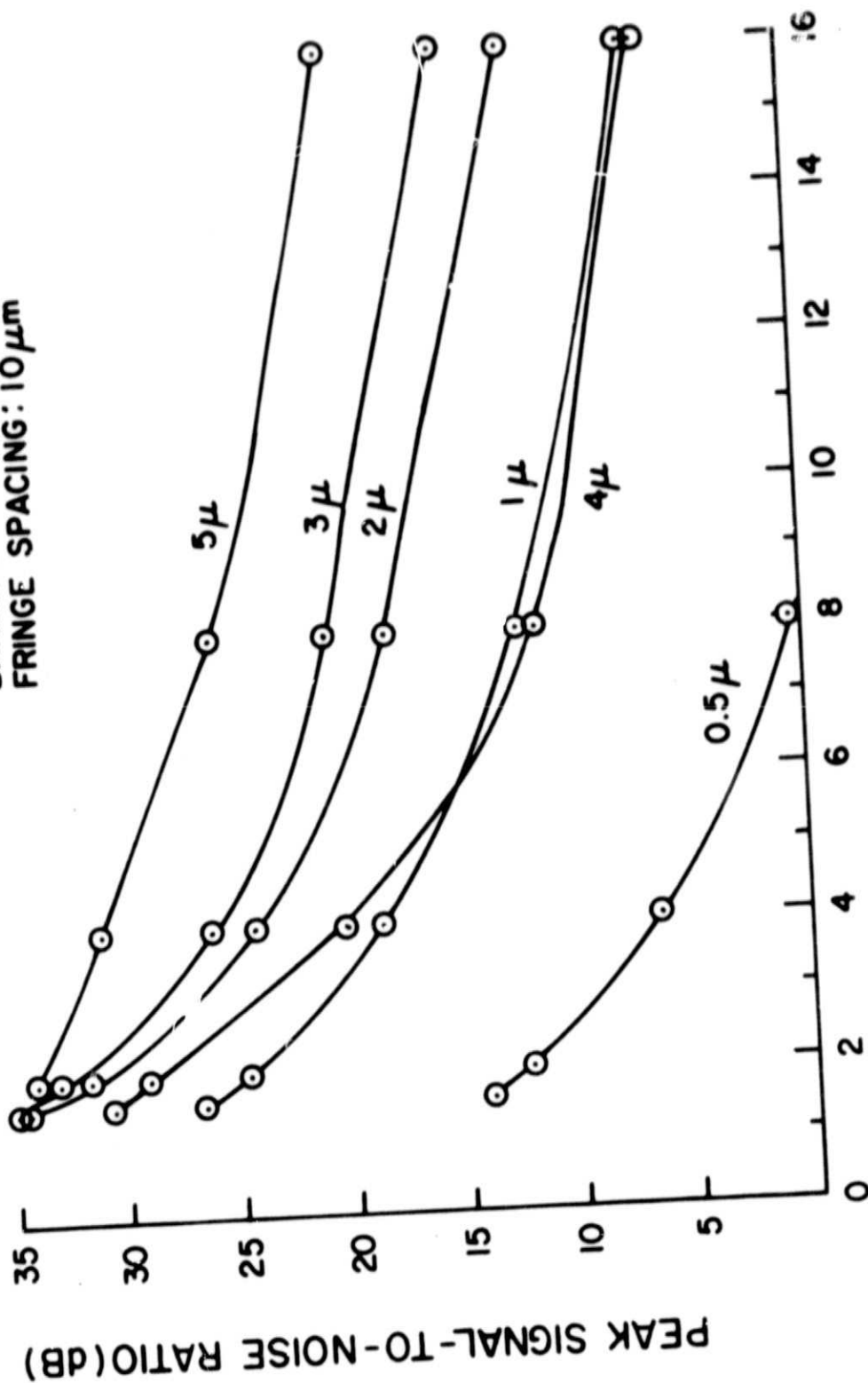
SAMPLE VOLUME



TYPICAL BURST SIGNAL

Figure 1. - Laser Velocimeter Technique

LASER OUTPUT POWER: 15mw
 BANDWIDTH: 29 MHz
 FRINGE SPACING: 10 μ m



F - NUMBER OF COLLECTING OPTICS

Figure 1A. - Signal-to-Noise Ratio as a Function of Collecting Optics
 F-Number for Various Particle Sizes.

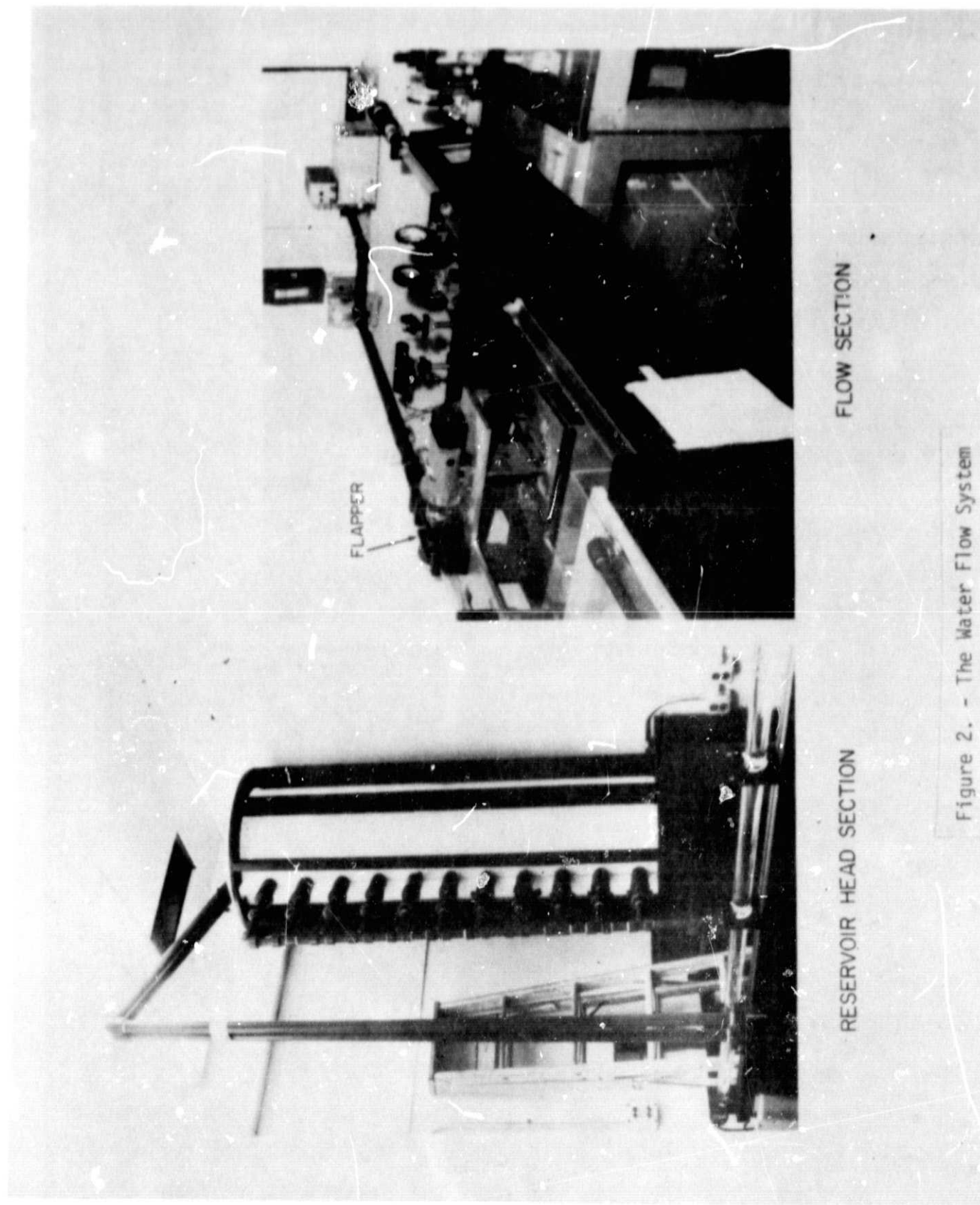


Figure 2. - The Water Flow System

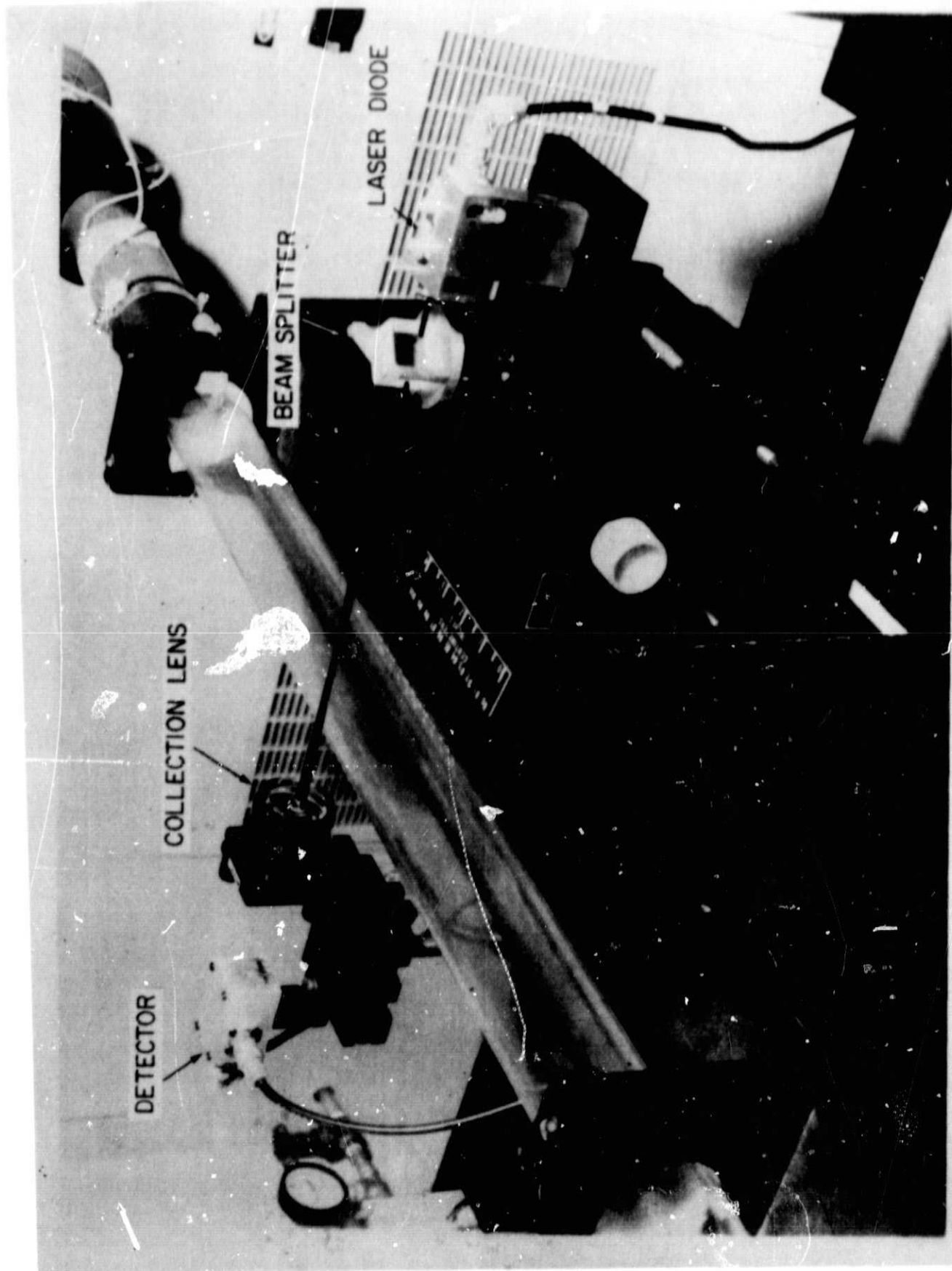


Figure 2A. - Prototype Forward Scatter Laser Diode Velocimeter in the Pipe Flow Laboratory.

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Figure 3. - The Laser Velocimeter

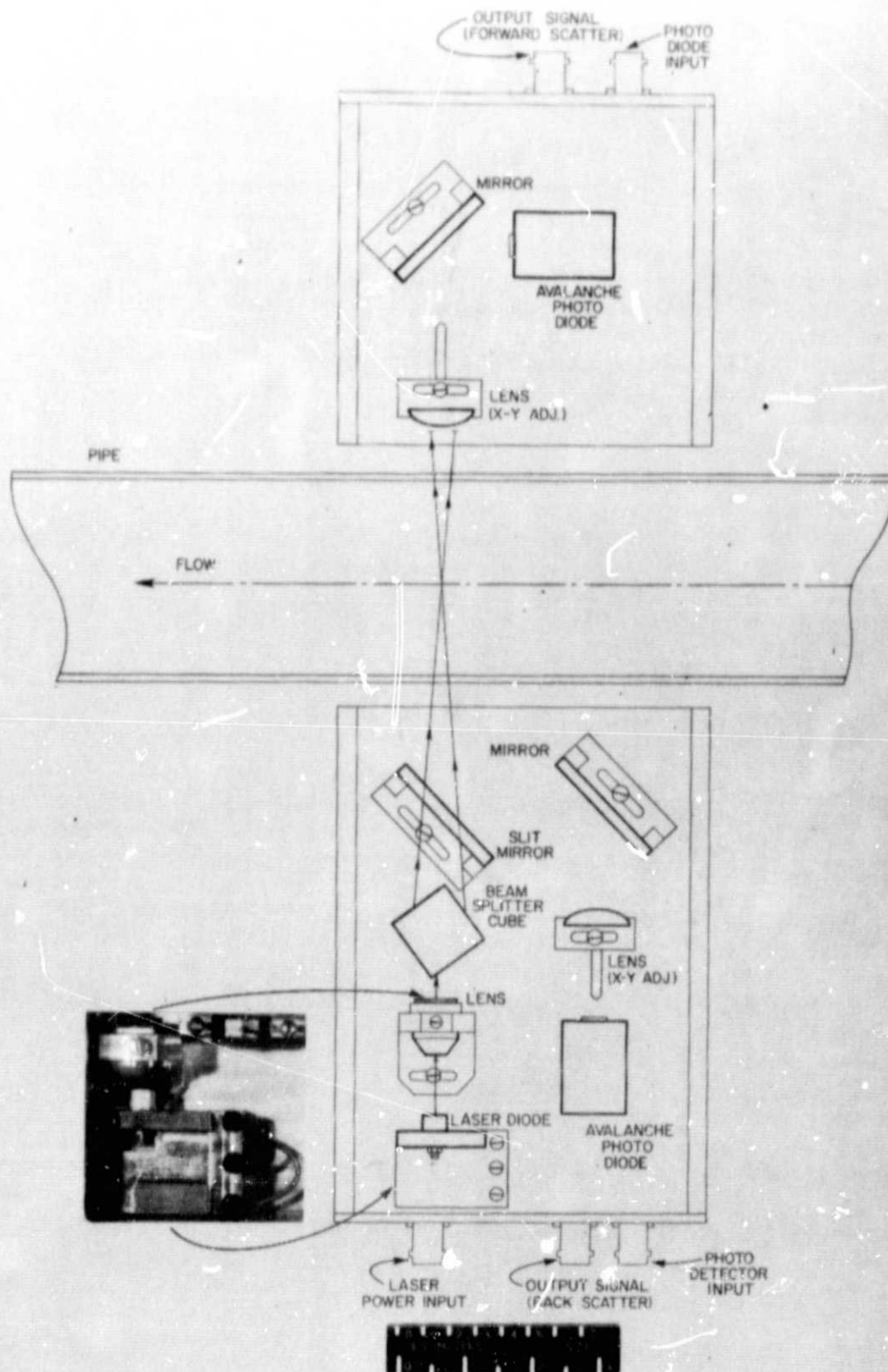


Figure 3A. - Proposed Laser Velocimeter System for POGO Flow Diagnostic System

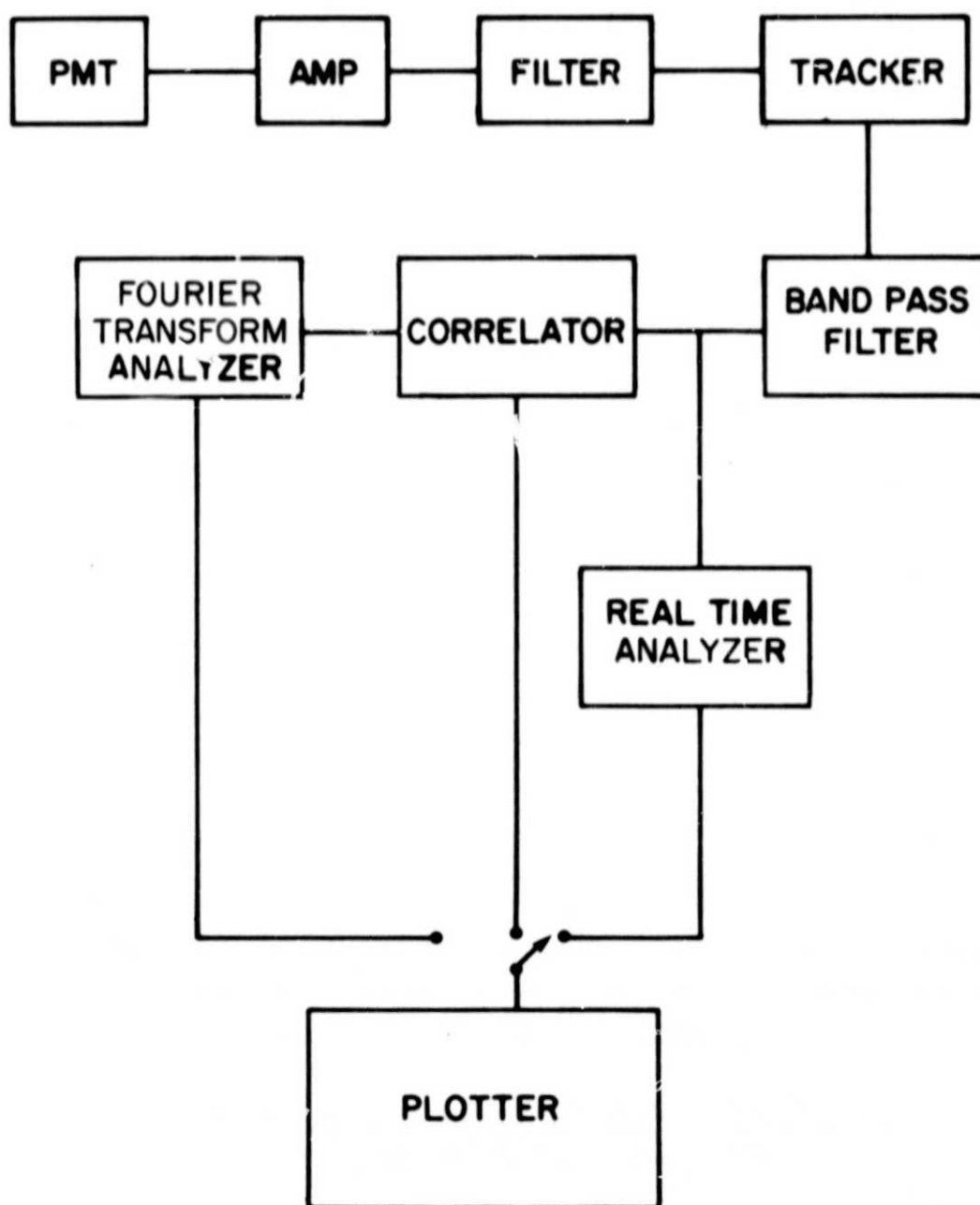
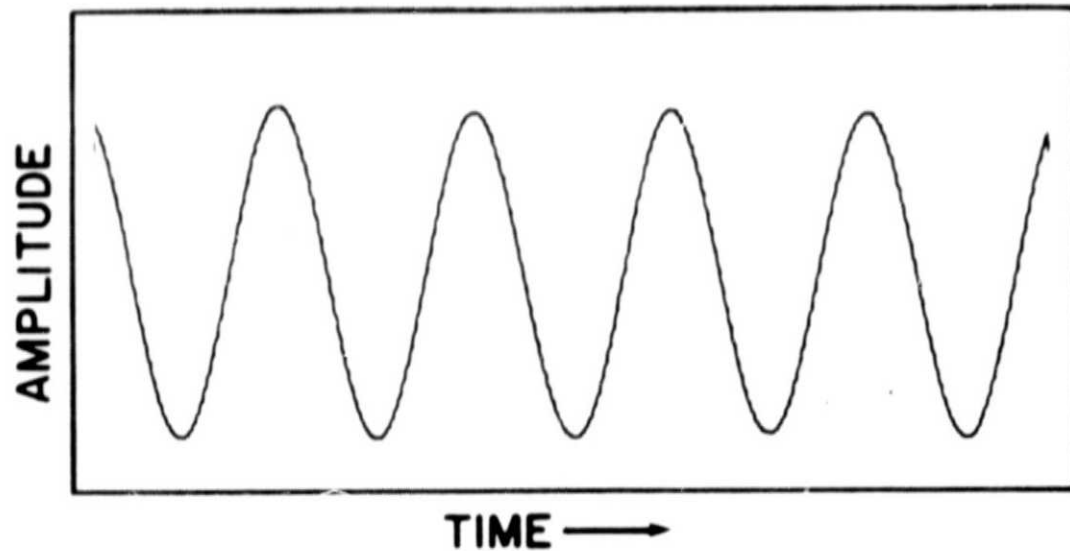
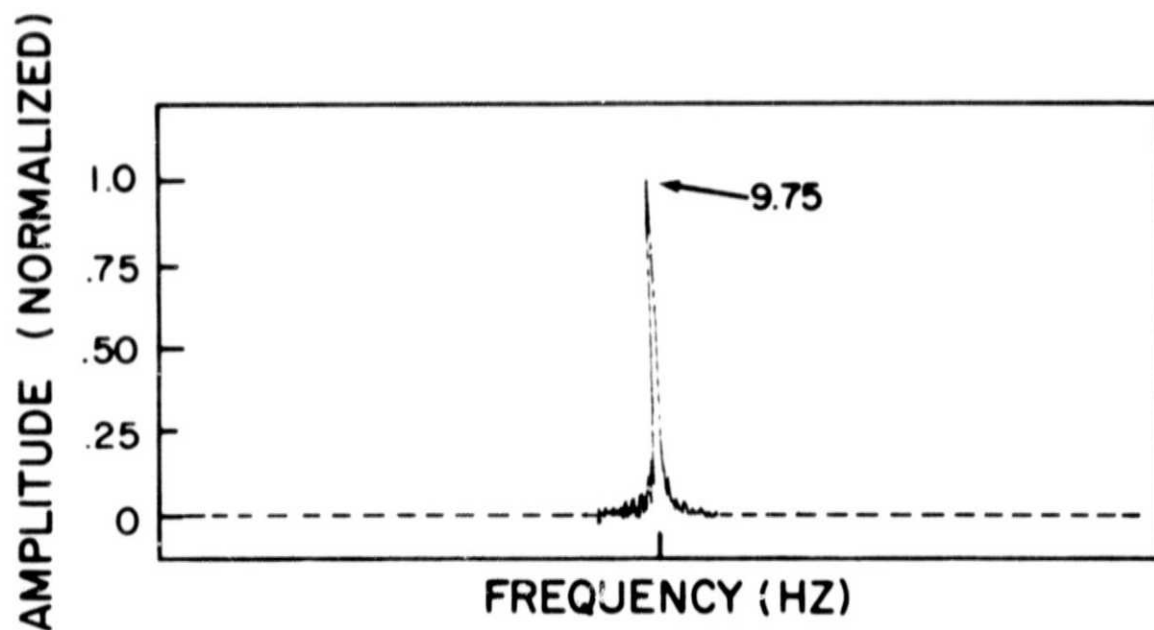


Figure 4. - A Block Diagram of the Data Processing Electronics

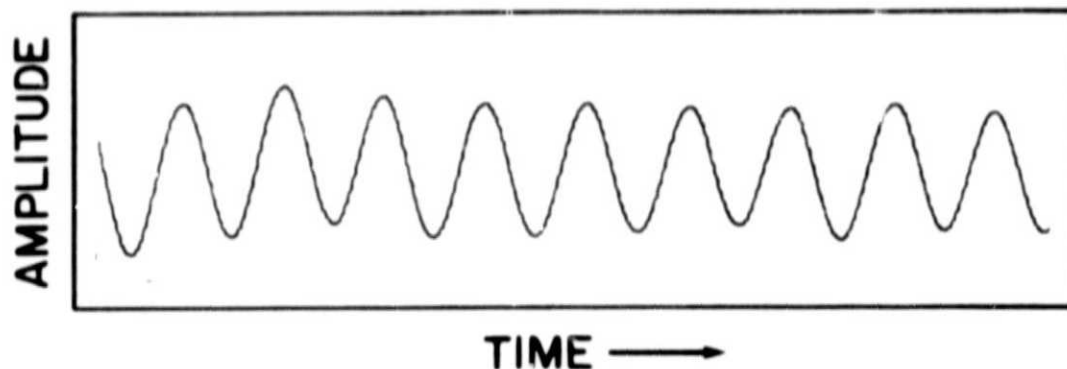


AUTO - CORRELATION FUNCTION

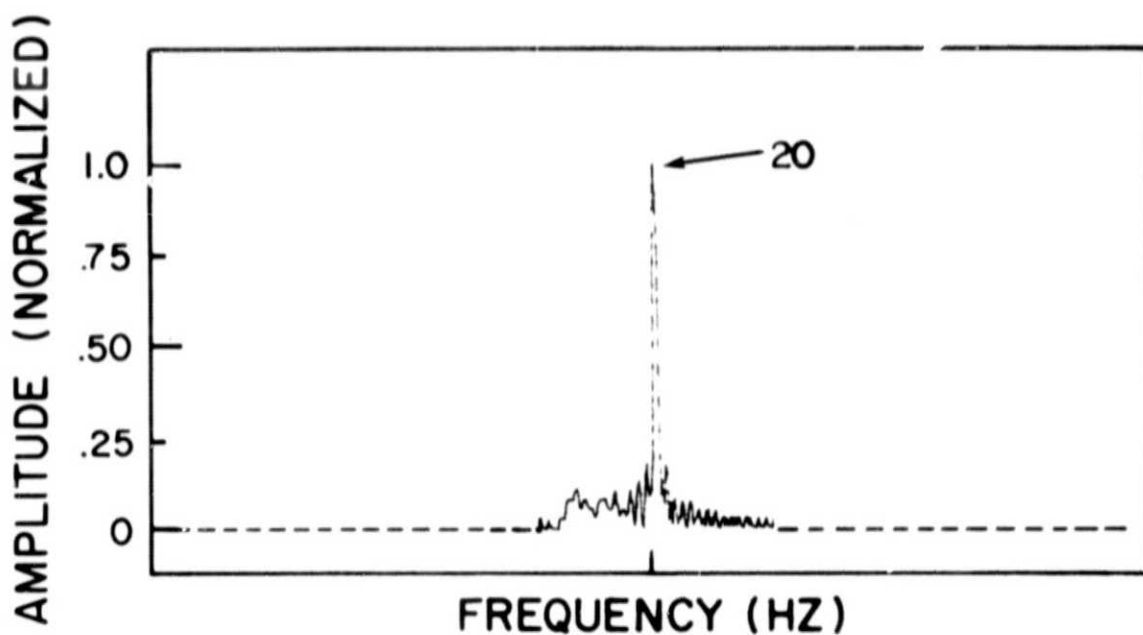


**FOURIER TRANSFORM FUNCTION
(POWER SPECTRUM)**

Figure 5. - The Auto-Correlation Function and Corresponding Power Spectrum for an Approximate 10 Hz Induced Flow Oscillation.

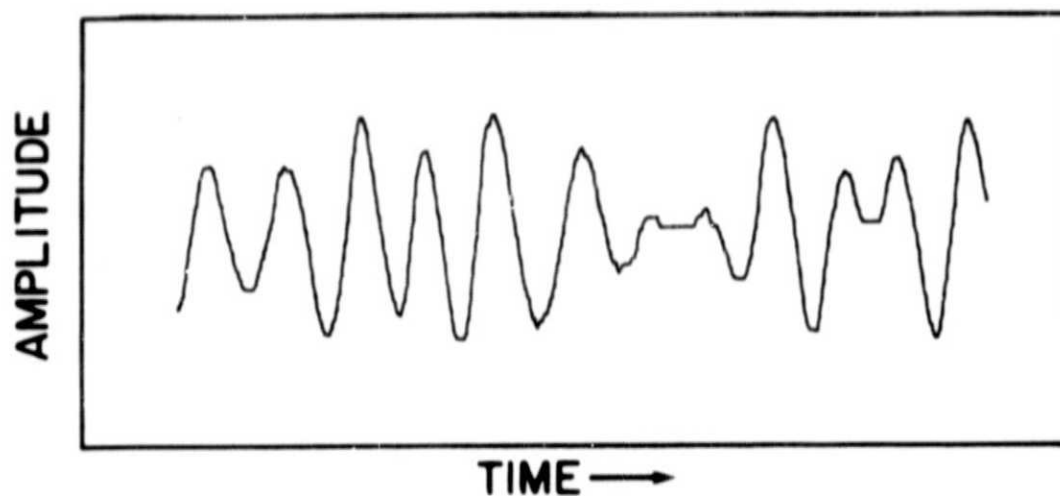


AUTO-CORRELATION FUNCTION

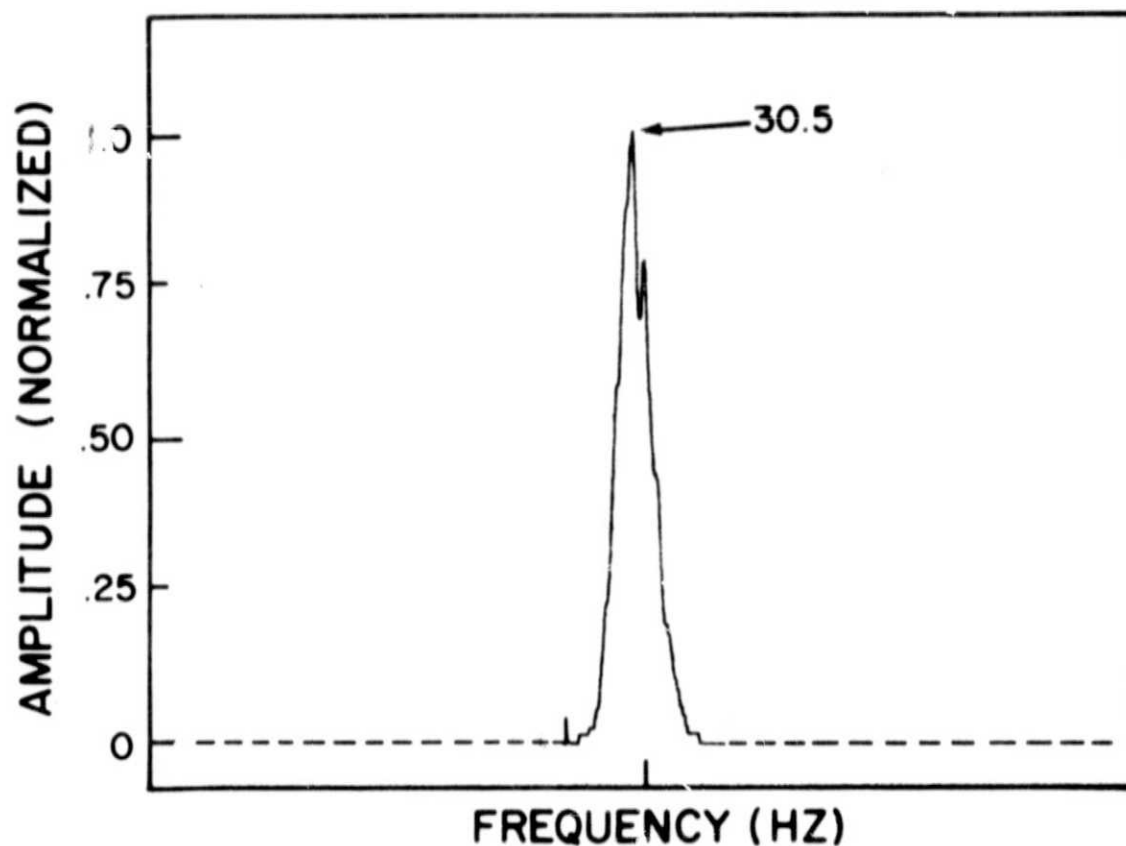


**FOURIER TRANSFORM FUNCTION
(POWER SPECTRUM)**

Figure 6. - The Auto-Correlation Function and Corresponding Power Spectrum for an Approximate 20 Hz Induced Flow Oscillation.

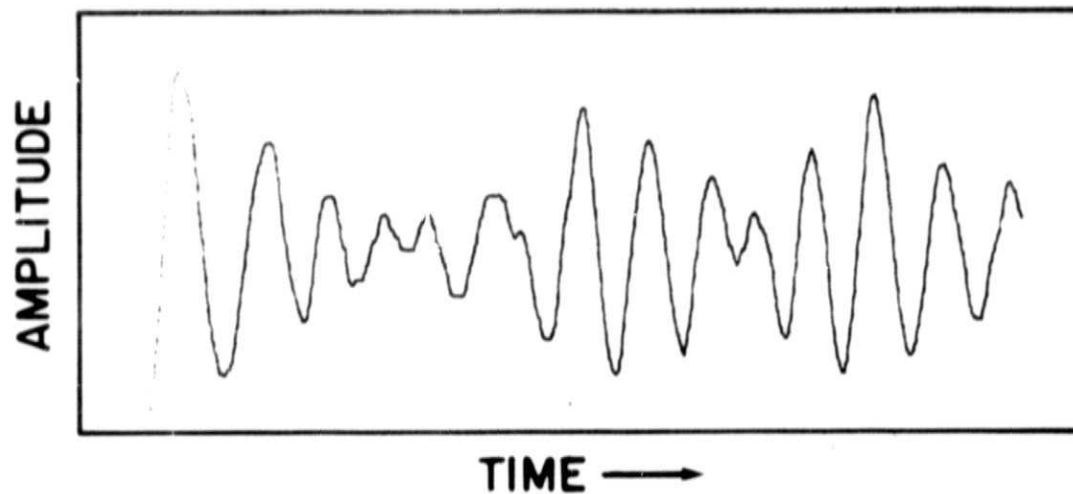


AUTO-CORRELATION FUNCTION

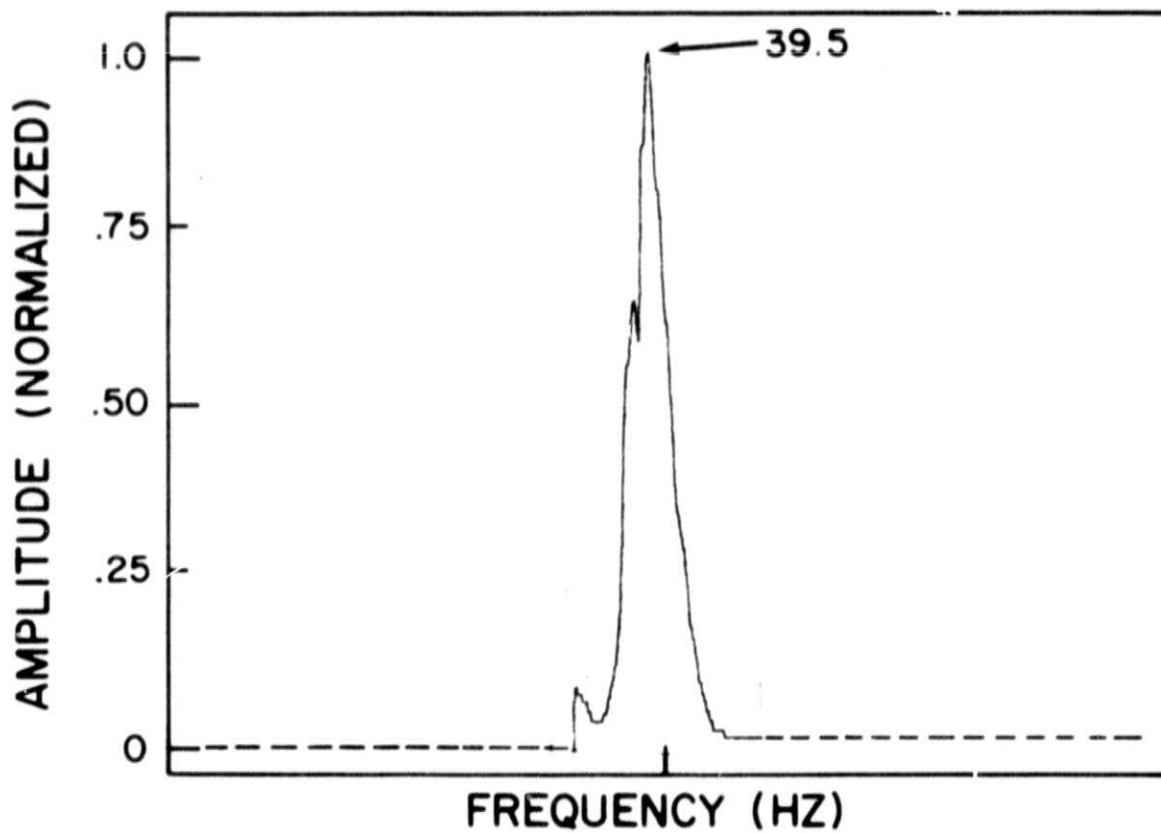


**FOURIER TRANSFORM FUNCTION
(POWER SPECTRUM)**

Figure 7. - The Auto-Correlation Function and Corresponding Power Spectrum for an Approximate 30 Hz Induced Flow Oscillation.



AUTO - CORRELATION FUNCTION



FOURIER TRANSFORM FUNCTION

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Figure 8. - The Auto-Correlation Function and Corresponding Power Spectrum for an Approximate 40 Hz Induced Flow Oscillation.

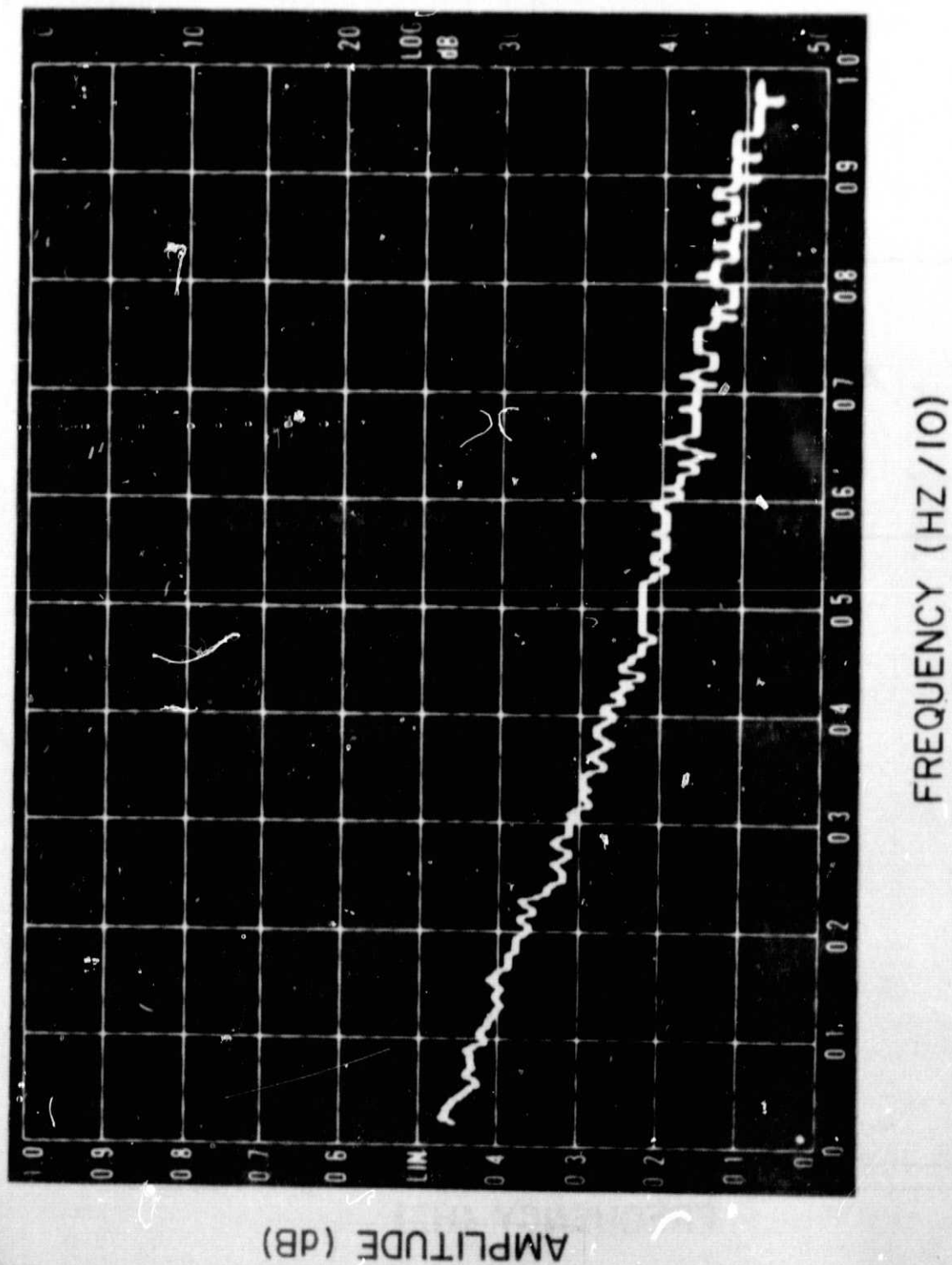
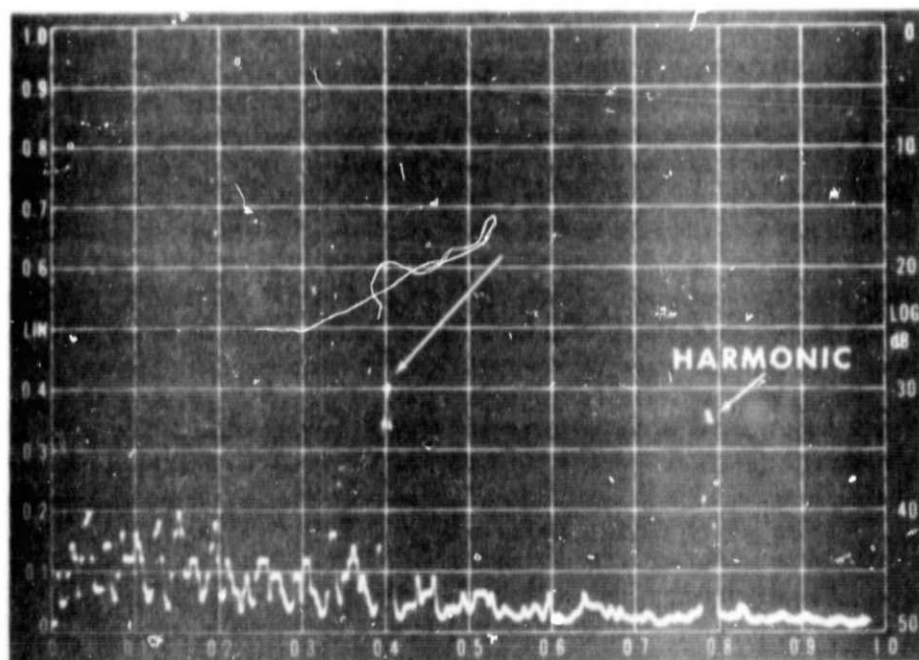


Figure 9.- Power Spectrum of an Approximate 2 m/s Flow Velocity
($N_R \approx 93,000$)

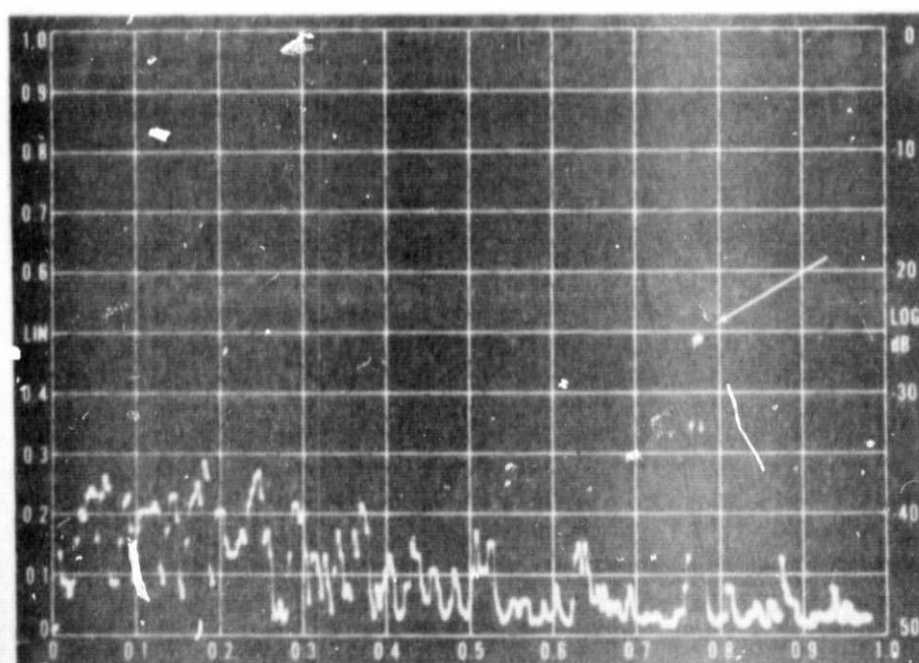
AMPLITUDE (dB)



FREQUENCY (HZ / 25)

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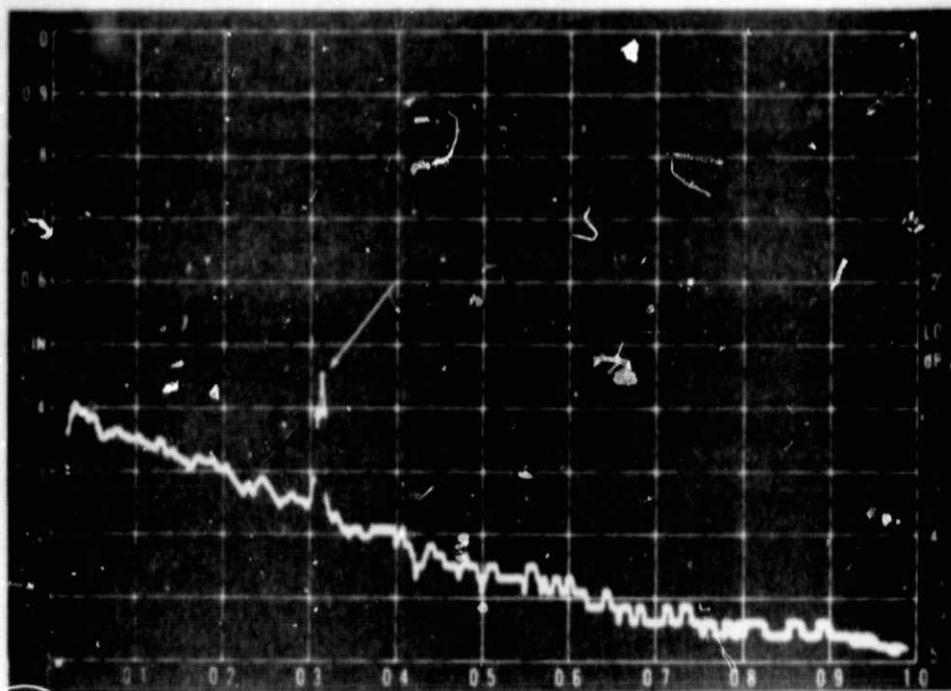
AMPLITUDE (dB)



FREQUENCY (HZ / 25)

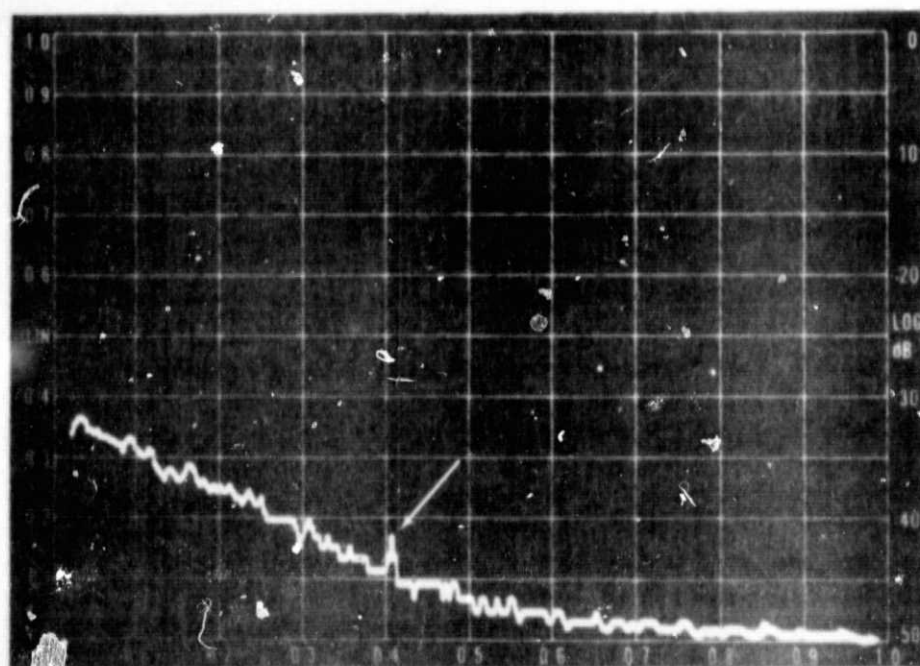
Figure 10. - Power Spectrum for a 10 Hz (Upper) and 20 Hz (Lower)
Induced Flow Oscillation.

AMPLITUDE (dB)



FREQUENCY (HZ / 10)

AMPLITUDE (dB)



FREQUENCY (HZ / 10)

Figure 11. - Power Spectrum for a 30 Hz (Upper) and 40 Hz (Lower) Induced Flow Oscillation.