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SPECTRAL ANAYLSIS OF CFB DATA

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Predictive Models of Circulating Fluidized Bed Combustors

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ABSTRACT

The overall objective of this investigation is to develop experimentally verified models for circulating fluidized bed (CFB) combustors.

Spectral analysis of CFB data obtained at IIT shows that the frequencies of pressure osillations are less than 0.1 Hertz and that they increase with solids volume fraction to the usual value of one Hertz obtained in bubbling beds. These data are consistent with the kinetic theory interpretation of density wave propagation:

C = psuedo-sound velocity = length x frequency. For CFB C = 10cm/sec, for bubbling beds, C = 1 m/s.

SPECTRAL ANALYSIS OF PRESSURE GRADIENT IN A CIRCULATING FLUIDIZED BED

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Introduction

Although much work has been published on Circulating Fluidized Beds and its applications, a systematic spectral analysis based on fluctuating pressure drop signals is still lacking-at least to the knowledge of the author. Tsuji et al. (1984) calculated spectrum of signals in a vertical pipe. However, their study was related to turbulence intensities of air and solids flows. The range of frequency in their work was from 2 to 10^4 H_z. Previous study of Tsuji et al. (1982) on pressure fluctuations was conducted in a horizontal pipe.

It is the purpose of this investigation to use the well-known Fast Fourier Transform (FFT) Technique to determine the dominant frequency of transient pressure gradients obtained from experimental studies by Miller, 1991 in which both solid flowrate and superficial gas velocity were independently manipulated. Compared with Tsuji et al., 1984, our spectrum computations are related to pressure drop signals in the low frequency range of 0 to 6 H_z. Pressure fluctuation changes with air velocity and solid flowrates are studied to discriminate between dilute and dense phase flow regimes.

Experimental Equipment

Since the experimental unit in this work, Figure 1, is identical as in Miller, 1991, only primary points are described here. The test section R (riser) was made of acrylic tube of 0.075 m i.d., with a length of 6.58 m. The particles are loaded at port A on the second floor and their feedrate was controlled by a slide valve V independently of the gas velocity. The gas distributor D, has an internal 38.1 mm, schedule 40, nozzle that distributes the flow into the riser. The particles flowing out from the test section were recovered by primary and secondary cyclones C through the upper U tube (U_u) and recirculated through the lower U tube (U_l). Several pressure taps along the height of the test section enabled us to measure the local pressure drop. A precise differential pressure transducer was used to obtain the pressure data. The output range of the transducer was 0-5 Volts for a pressure range from 0-10 inch of water. Fluid Cracking Catalyst (FCC) particles of 1.0 g/cm^3 density and size ranging from 10-200 μm was used in the experiments. The highest superficial gas velocity and solid feed rate were 3.48 m/s and 32.8 Kg/($m^2.s$) respectively. Experiments were carried out by reducing the air flow rate at constant solid feed rate and vice versa. The sampling frequency of the pressure drop signal was F_s=12 H_z which corresponds to a Nyquist frequency F_n (F_n= (F_s)/2) of 6H_z. Maximum frequency of the pressure fluctuations was limited to the Nyquist frequency.

Results and Discussion

To characterize the flow regimes, both static and fluctuating components of the local pressure drop were measured in the riser upper part (ΔP_u), between taps 1 and 2 and lower part (ΔP_l), between taps 2 and 3. Figure 2 illustrates dependence of local pressure drops (ΔP_u and ΔP_l) on superficial gas velocity (U_g) for a flux of 20.4 Kg/($m^2.s$). ΔP_u and ΔP_l were obtained by averaging instantaneous pressure over 150 s. The local pressure drop at the bottom of the bed, ΔP_l, increases with decreasing U_g. However, the local pressure drop ΔP_u measured above the bubbling bed level first decreases with decreasing U_g then increases with decreasing U_g.

Wave Form Analysis of Pressure Fluctuation.

Figure 3 shows the wave form of instantaneous differential pressure in the upper section of each flow regime under study (dense, transition, and dilute), where ΔP_u is given in inch of water. In this test series the gas velocity was held constant at 2.89 m/s and the solid flow rate was increased in steps.

At the lowest circulation rate, F=12.0 Kg/($m^2.s$), there is no evidence of a two phase structure to the flow. The capacitance trace shows a uniform fluctuation with negligible amplitude associated with passage of dilute phase around the probe tip (Figure 3a)

At higher circulation rate of 20.4 Kg/($m^2.s$) a two phase character becomes evident due to the presence of a slug. Figure 3b shows a typical pressure fluctuation in this flow condition.

At the highest circulation rate of 32.8 Kg/($m^2.s$) there is a well defined two phase structure to the flow. A vigorous refluxing of solids could be observed along the wall with a dense boundary layer. Figure 3c shows a more pronounced fluctuations in the dense flow regime with higher amplitude of oscillations.

Figure 4 shows similar trend of pressure fluctuations in the lower section of the riser except that at the circulation rate of 20.4 Kg/($m^2.s$) no slug was observed at least over the first 150 seconds.

Spectral Analysis of Pressure Fluctuations.

A preliminary test was performed in this study to determine that the data were obtained under the stationary conditions in terms of statistical analysis. This analysis was performed with a typical recorded signal taken with a total sampling time of 150 seconds. The signal was divided into three sets of data with total sampling times of 100, 125, and 150 seconds each. The mean and standard deviation of each set of data were calculated and compared. It was observed that the mean varies about 0.1 % for 100 and 150 seconds. Considering these results the recorded signals taken with identical sampling time of 150 s are stationary signals which can therefore be analyzed in domains of time and frequency. The maximum frequency obtainable in this study is the Nyquist frequency of 6 H_z.

Figure 5 shows a typical pressure signal obtained in the dilute phase flow regime. Pressure fluctuations in this regime are extremely small. The power spectral density function of the data is shown in Figure 6. A dominant frequency is observed at 0.006 H_z while the spectral density is zero for frequencies up to 6 H_z. The dominant frequency corresponds to a period T= 150 seconds which is the total sampling time. Since our study was restrained to frequency below 6 H_z, high frequencies may well exist.

The bed operates in the dilute phase flow regime at the FCC flow rate of 12.0 Kg/($m^2.s$) and superficial air velocity of 2.89 cm/s as is evident from the pressure fluctuations shown in Figure 5.

When the particles flowrate is increased to 20.4 Kg/($m^2.s$), the pressure fluctuations become pronounced as shown in Figure 7 for the bed operated at the superficial air velocity of 2.89 m/s. The peak indicates the presence of a slug. Figure 8 shows the power spectral density function of this set of data. Some higher frequencies are found to exist in the signal and the dominant frequency is 0.023 cycles/s.

When the flowrate is further increased to 32.8 Kg/($m^2.s$), the dense layer is found to grow. Figure 9 shows a typical sample of data obtained in the dense phase flow condition. It is apparent that the fluctuations are much larger compared with previous runs. Figure 10 shows the power spectral density function for the same set of data. The dominant frequency is 0.05 H_z. The variation of dominant frequency of the pressure fluctuations with superficial air velocity is shown in Figure 11. It is noted that the frequency increases with solids solids flowrate.

Figures 12 and 13 show the pressure fluctuation and their power spectral function for the upper section of the riser. The flowrate was held constant at 20.4 Kg/($m^2.s$) while the superficial gas velocity decreased from 3.48 m/s to 2.6 m/s. This trend has been observed by other investigator (Satija et al., 1985)

Pressure fluctuations and corresponding spectral function of data set for the bottom riser are also shown in Figures 14, 15, and 16 where the velocity was held at 2.89 m/s and the solids flow rate was decreased from 12.0 Kg/($m^2.s$) to 32.8 Kg/($m^2.s$)

Sensitivity Analysis.

In this study, an International Mathematical and Statistical (IMSL) subroutine was called to compute the power spectra of time series via Fast Fourier Transform. In the subroutine, spectral estimates are taken to be at the following frequencies:

$$f_i = \frac{i-1}{L\,\Delta t} \qquad i = 1, 2, \ldots, (\frac{L}{2}) + 1$$

where Δt is the period of sampling of the time series, L is an input parameter used to segment the time series and must be a power of two. Figure 17 shows the spectral density function for two value of L: L=2^6, and L=2^7. It is now clear that to detect low frequencies, it is crucial to use high values of L i.e. small increment of the frequencies. Other investigators (Tsuji et al., 1982; Satija et al., 1985) were unable to obtain such low frequencies.

Figure 18 shows the variation of dominant frequency in function of solids volume fraction (ϵ_s) near the wall in both circulating and bubbling fluidized beds. The frequency increases with an increase of ϵ_s. Similar trend was observed for the solids elastic modulus with respect to ϵ_s (Gidaspow, 1986). An attempt is underway to obtain an expression of the particle-particle interaction coefficient in terms of ϵ_s through the frequency f(ϵ_s) and the wavelenght.

Conclusions

Fast Fourier Transform (FFT) technique was used to determine the dominant frequency of transient pressure gradients obtained from experimental studies in which both solid flowrate and superficial gas velocity were indepently manipulated. Frequencies were found to vary in the range of 0.006 to 0.1 H_z.

Pressure fluctuation changes with air velocity and solid flowrates were studied to discriminate between dilute and dense phase flow regimes. For a constant superficial gas velocity of 2.89 m/s, the solid flowrate was increased in steps.

At the lowest circulation rate, F=12.0 Kg/($m^2.s$), there is no evidence of a two phase structure to the flow; the capacitance trace shows a uniform fluctuation with negligible amplitude associated with passage of dilute phase around the probe tip.

At higher flux, F=20.4 Kg/($m^2.s$), a two phase character becomes evident due to the presence of a slug.

At the highest circulation rate of 32.8 Kg/($m^2.s$), there is a well defined two phase structure to the flow; since pressure fluctuation is more pronounced with higher amplitude of oscillations.

The shape of the spectral density function was found to be dependent of an input parameter L used to segment the time series. It is clear that high values of L is needed to detect low frequencies. Other investigators (Tsuji et al., 1982; Satija et al., 1985) were unable to obtain such low frequencies.

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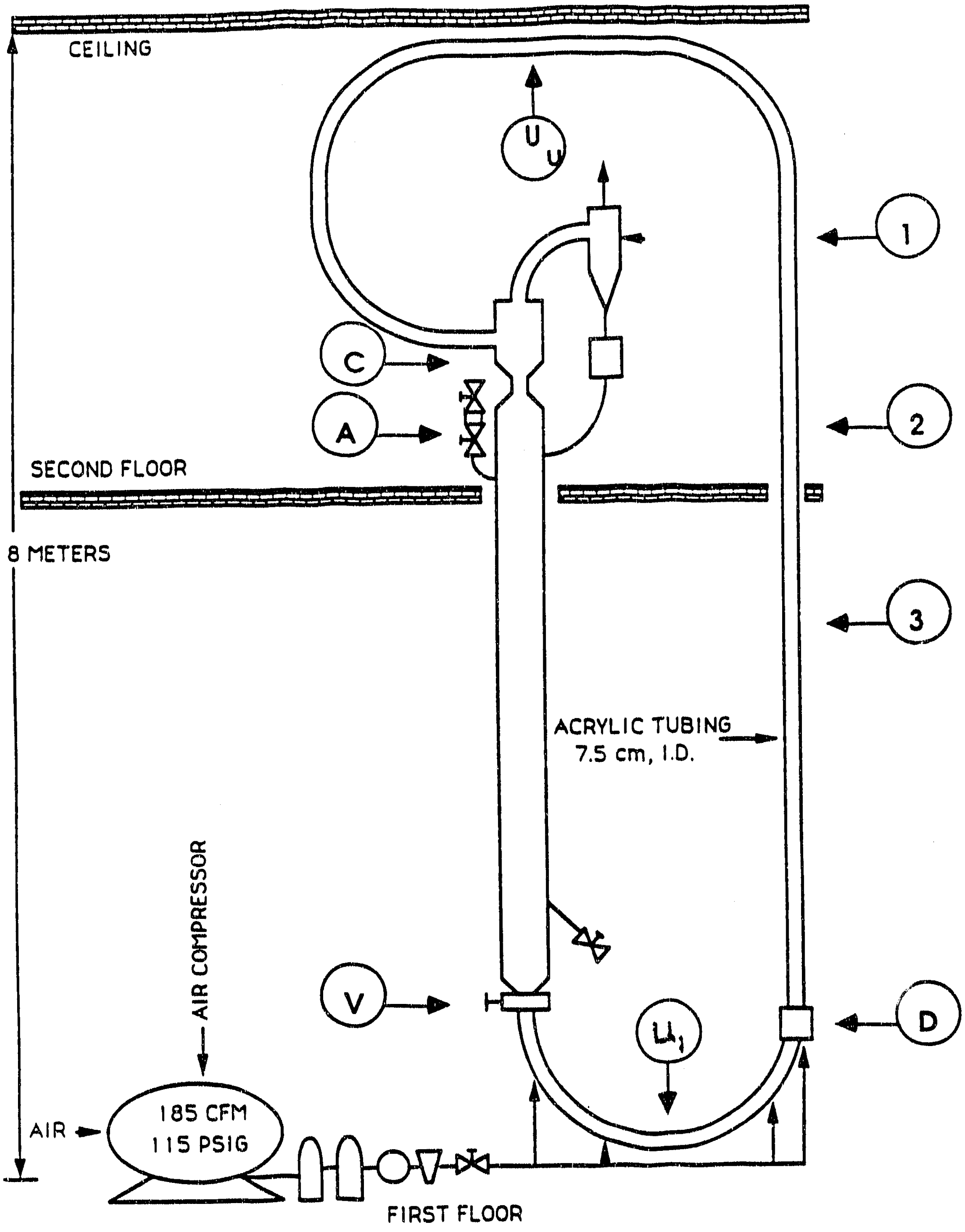


Figure 1. Schematic Diagram of Circulating Fluidized Bed

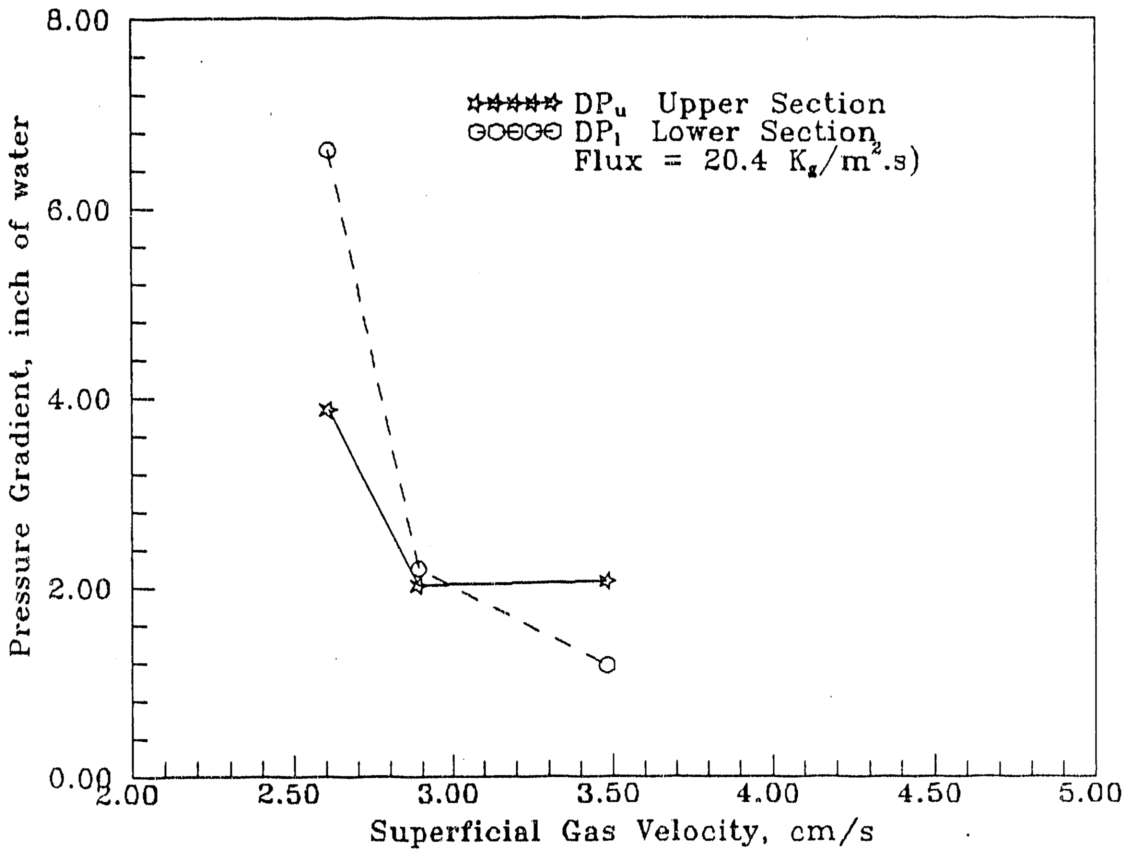


Figure 2. Local Static Pressure Drop as a Function of Superficial Velocity

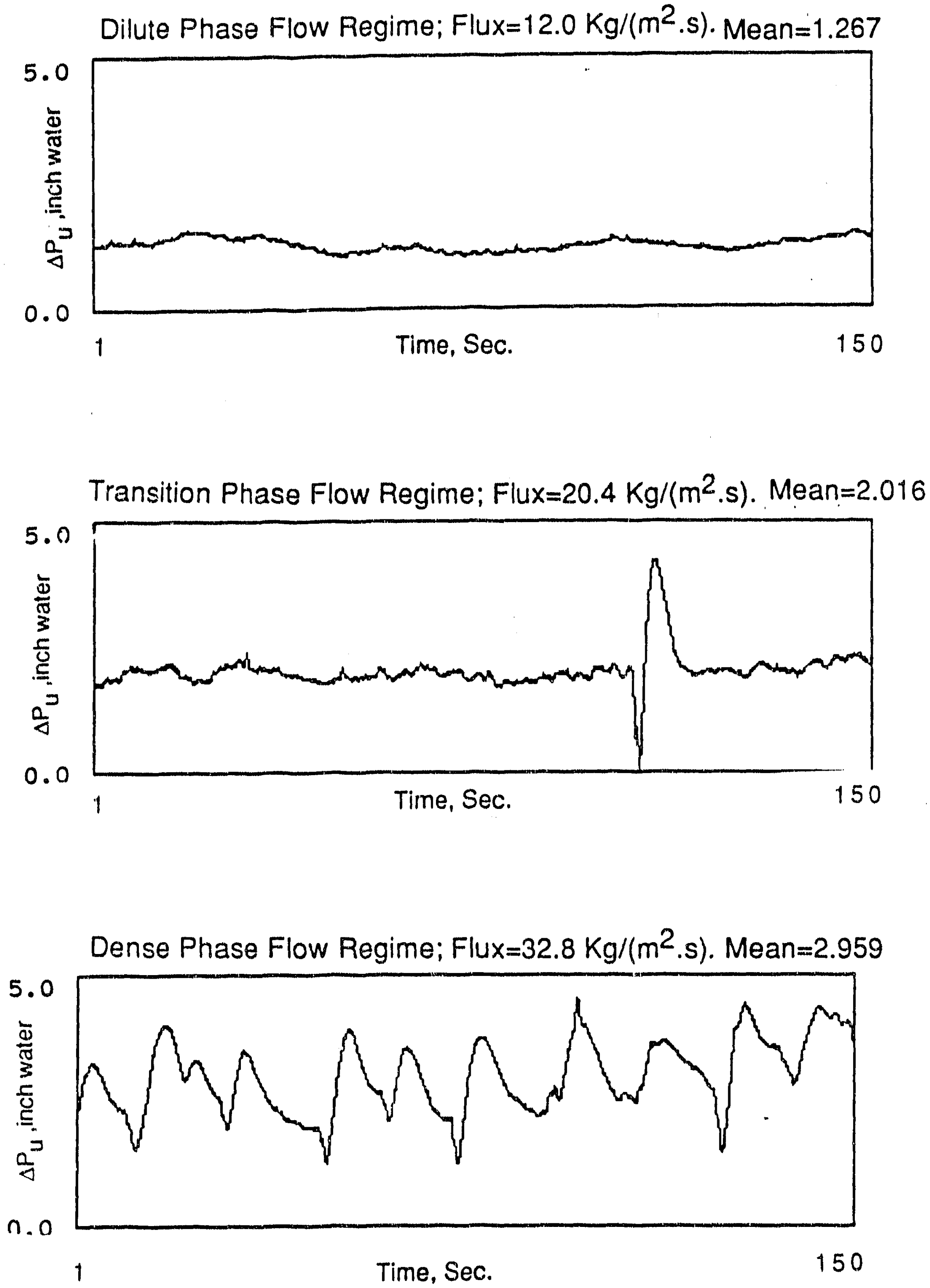


Figure 3. Pressure Fluctuation in the Upper Section of the Riser (U_g=2.89 m/s)

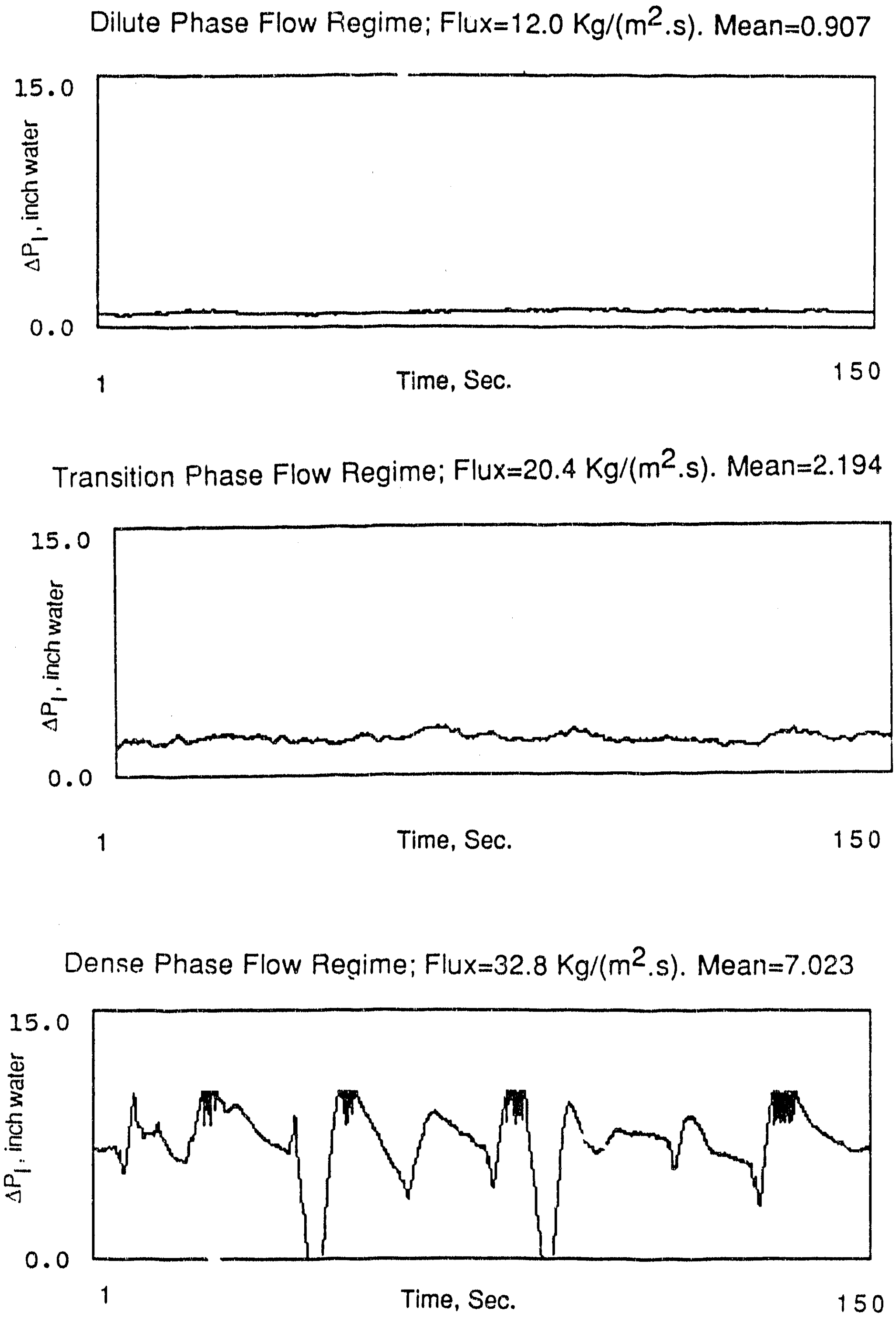


Figure 4. Pressure Fluctuation in the Lower Section of the Riser (U_g=2.89 m/s)

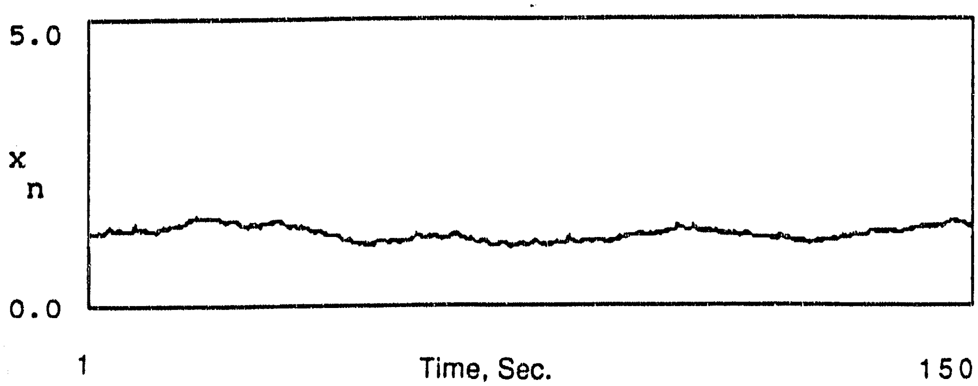


Figure 10.5. Pressure Fluctuation for Dilute Phase Flow of FCC. $F=12.0\ Kg/(m^2.s)$; $U_g=2.89$ m/s

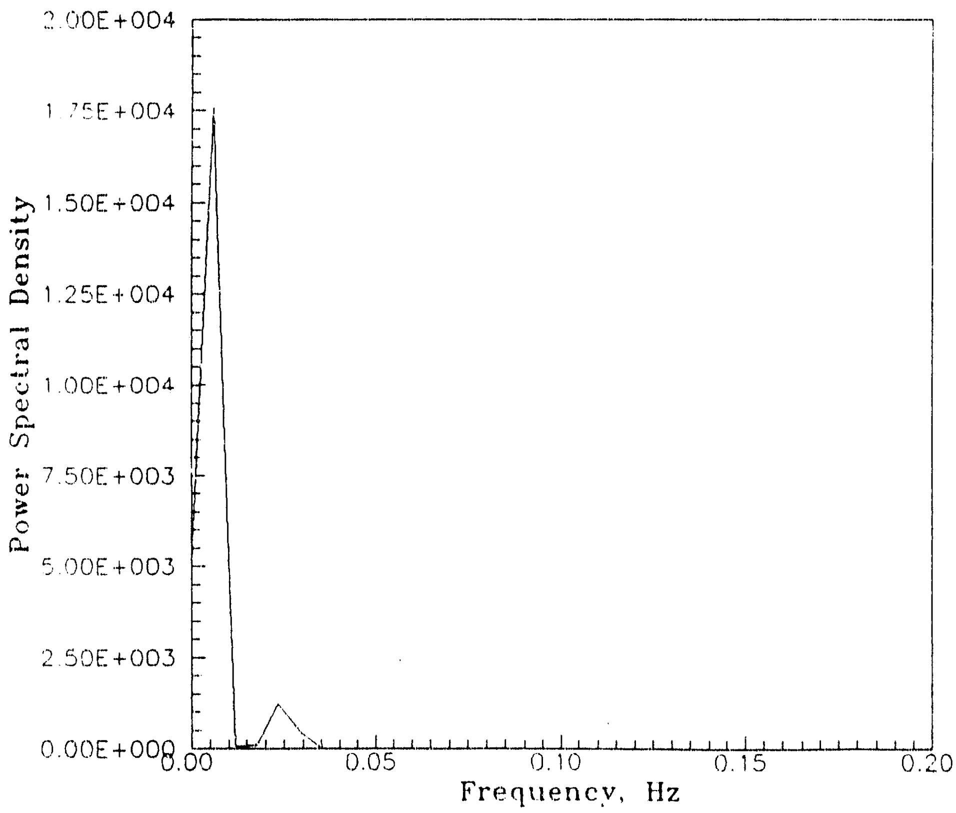


Figure 6. Power Spectral Density Function of Pressure Oscillations for Dilute Phase Flow of FCC. $F=12.0\ Kg/(m^2.s)$; $U_g=2.89$ m/s

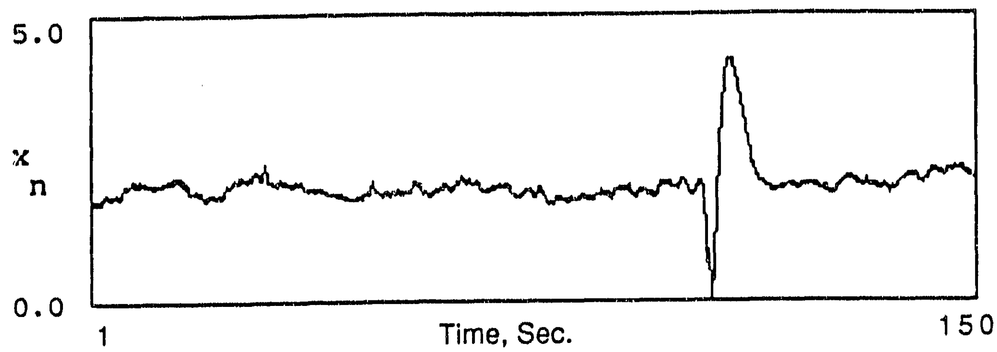


Figure 10.7. Pressure Fluctuation for Transition Phase Flow of FCC.
F=20.4 Kg/(m^2.s); U_g=2.89 m/s

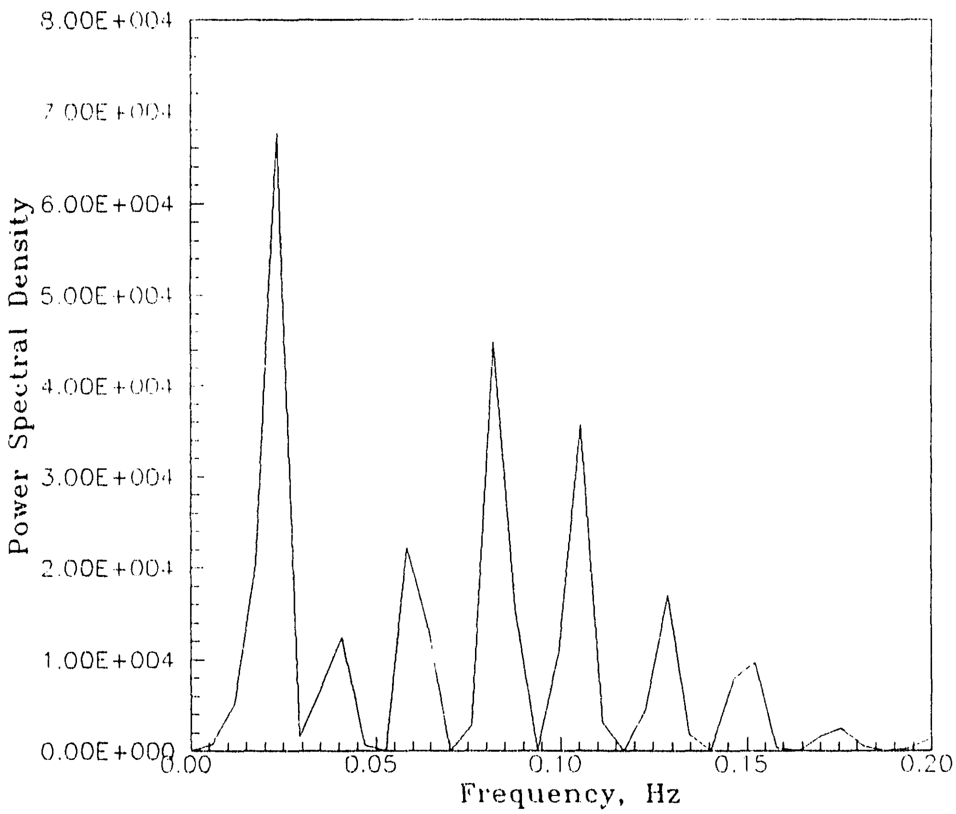


Figure 8. Power Spectral Density Function of Pressure Oscillations for Transition Phase Flow of FCC. F=20.4 Kg/(m^2.s); U_g=2.89 m/s

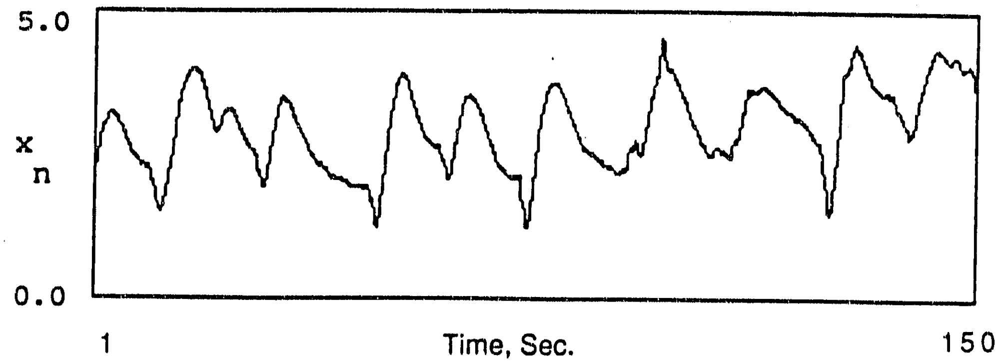


Figure 10.9. Pressure Fluctuation for Dense Phase Flow of FCC. $F=32.8$ Kg/(m^2.s); $U_g=2.89$ m/s

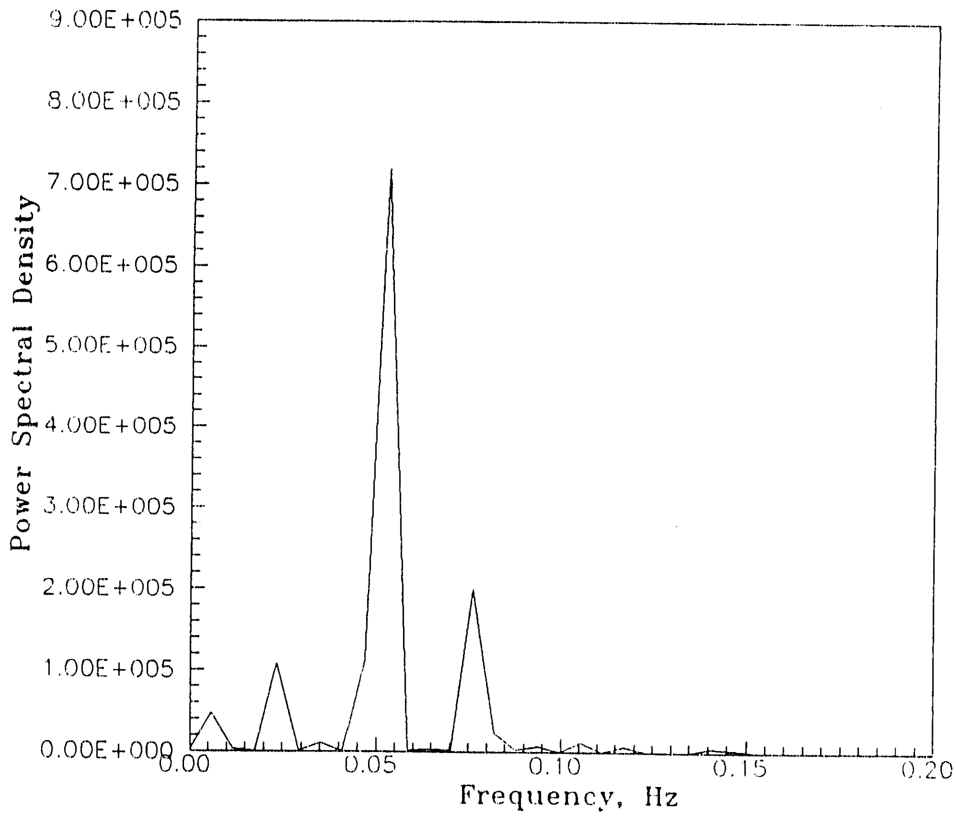


Figure 10. Power Spectral Density Function of Pressure Oscillations for Dense Phase Flow of FCC. $F=32.8$ Kg/(m^2.s); $U_g=2.89$ m/s

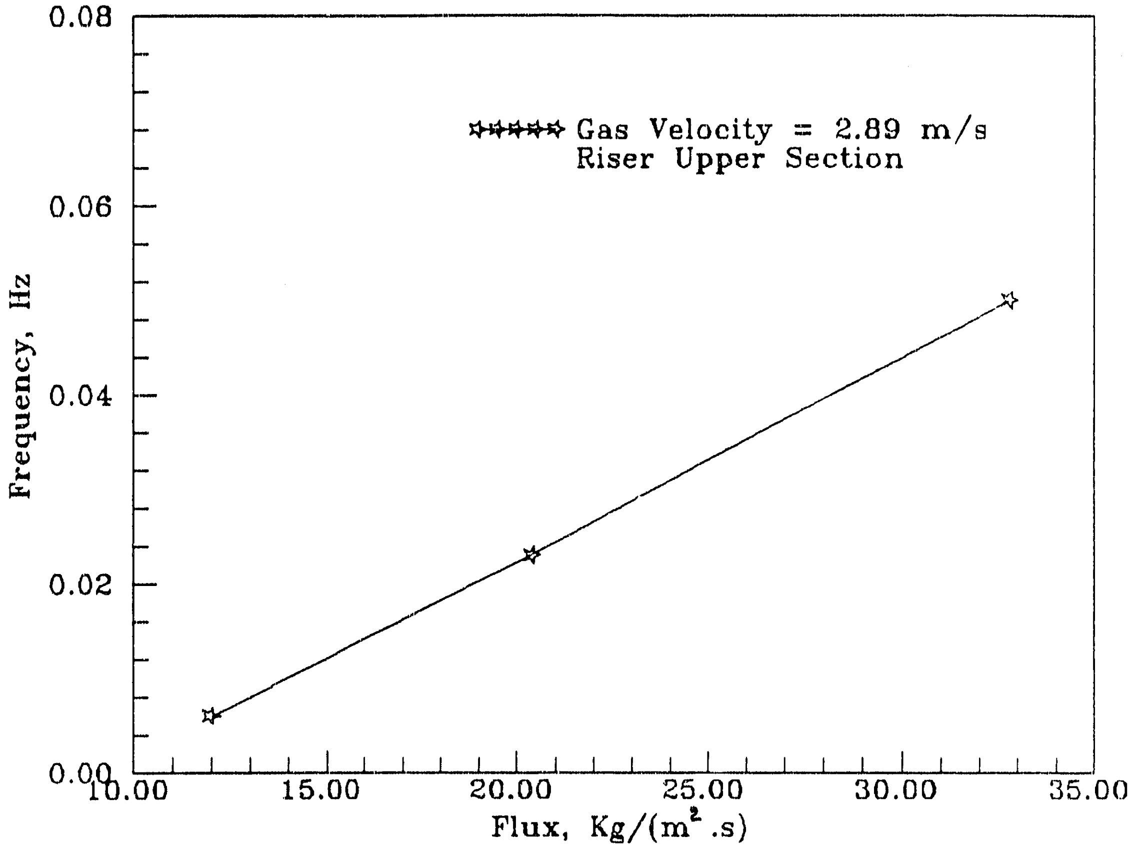


Figure 11. Dominant Frequency Vs. Solids Flowrate

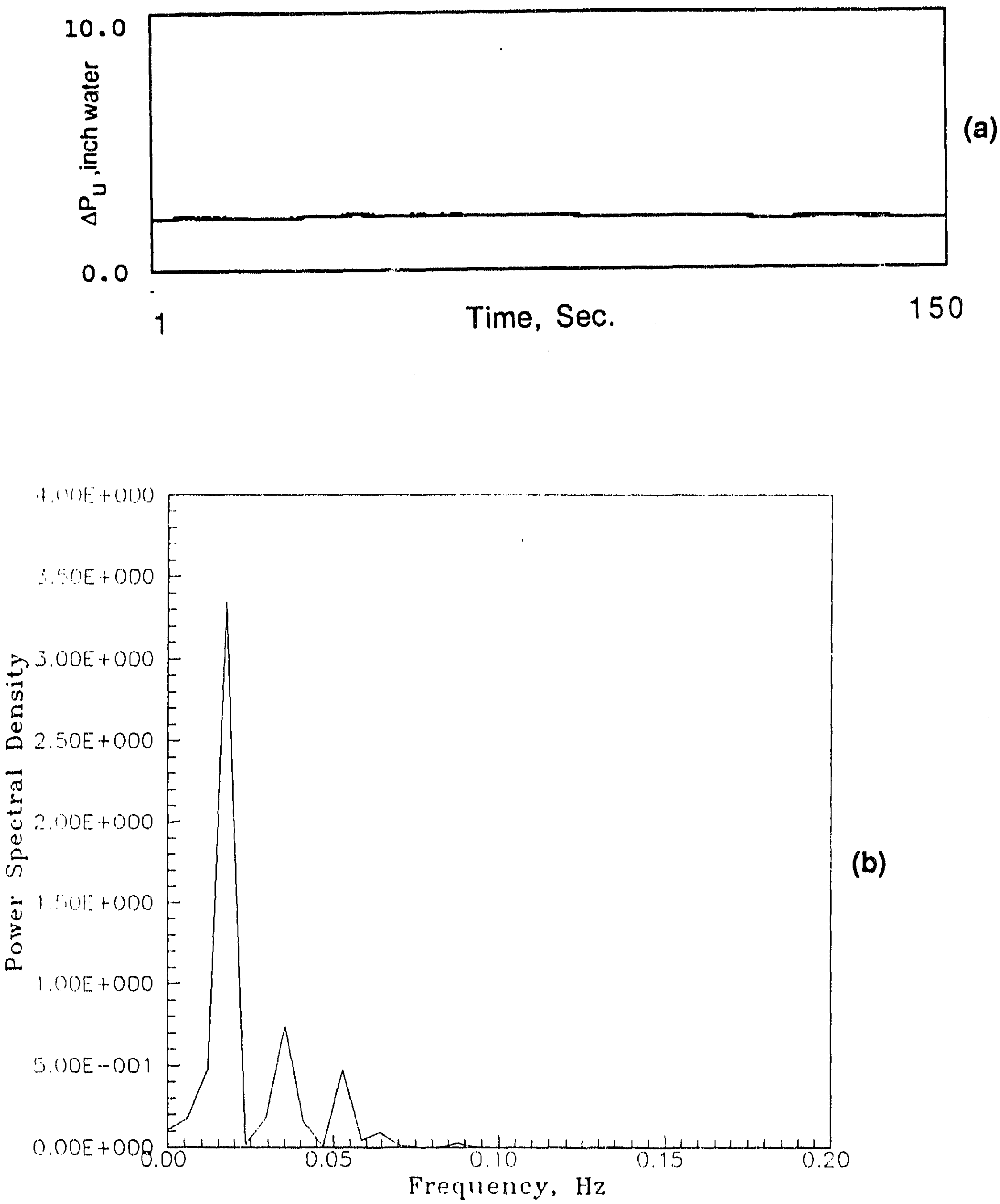
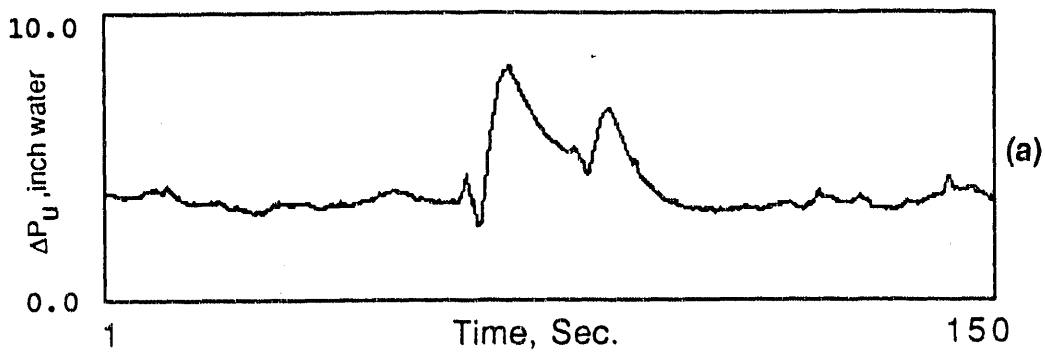


Figure 12. Pressure Oscillations (top), and Corresponding Spectral Density Function (bottom) in the Upper Section [U_g=3.48 m/s; F=20.4 Kg/(m^2.s)]



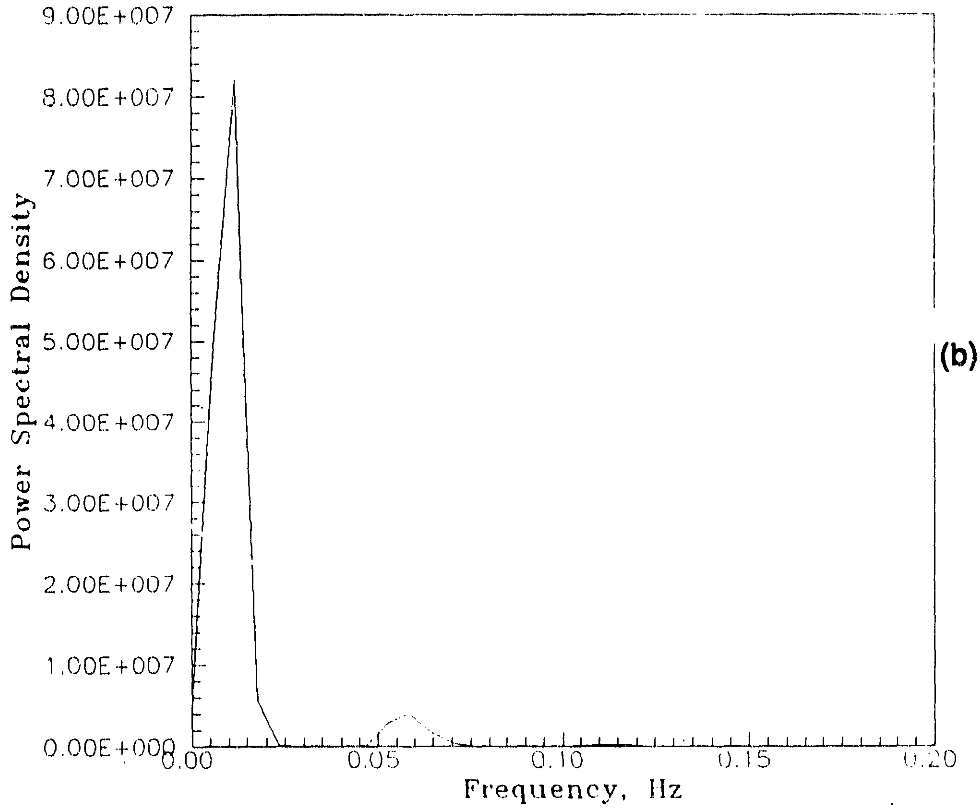
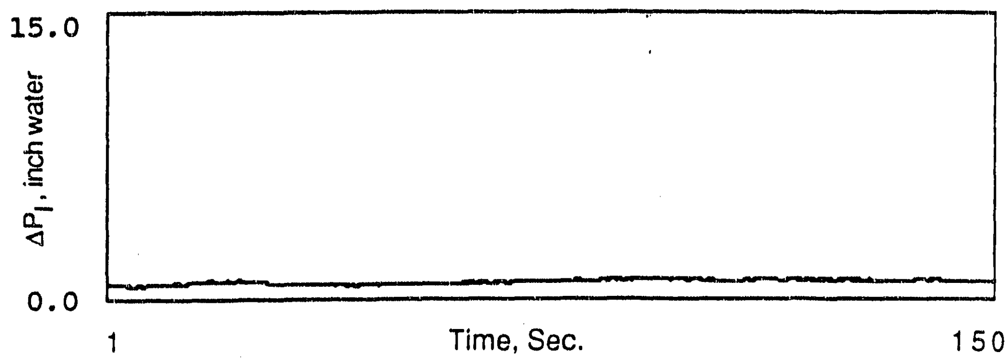


Figure 13. Pressure Oscillations (top), and Corresponding Spectral Density Function (bottom) in the Upper Section [U_g=2.61 m/s; F=20.4 Kg/(m^2.s)]



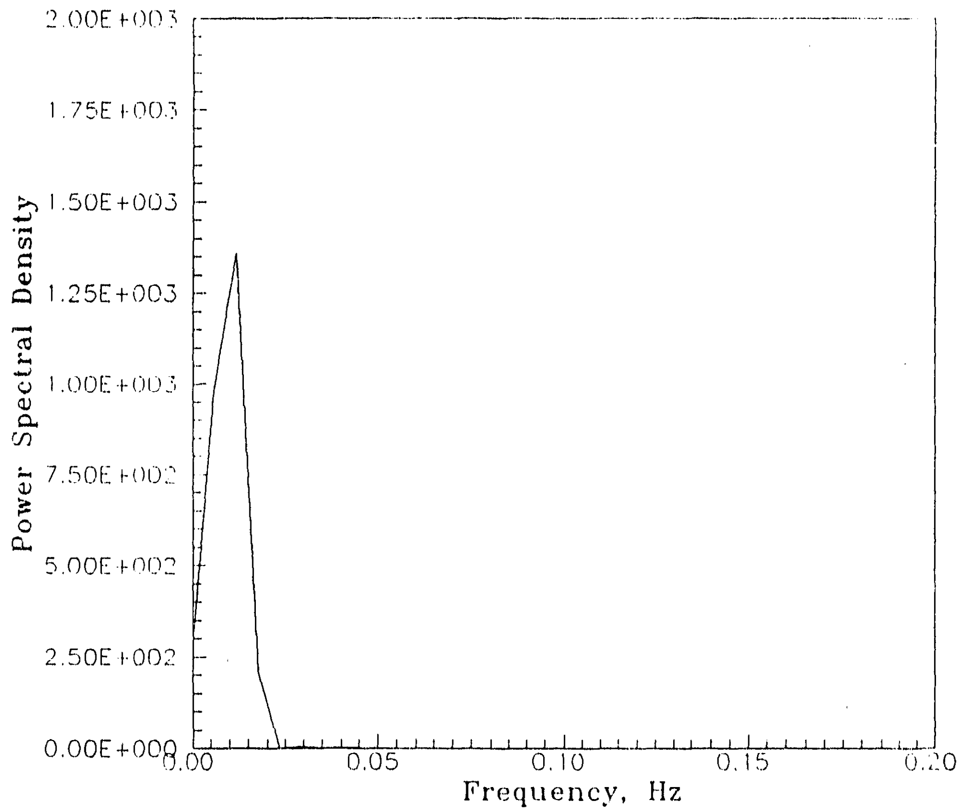


Figure 14. Pressure Oscillations (top), and Corresponding Spectral Density Function (bottom) in the Lower Section [F=12.0 Kg/(m^2.s);U_g=2.89 m/s]

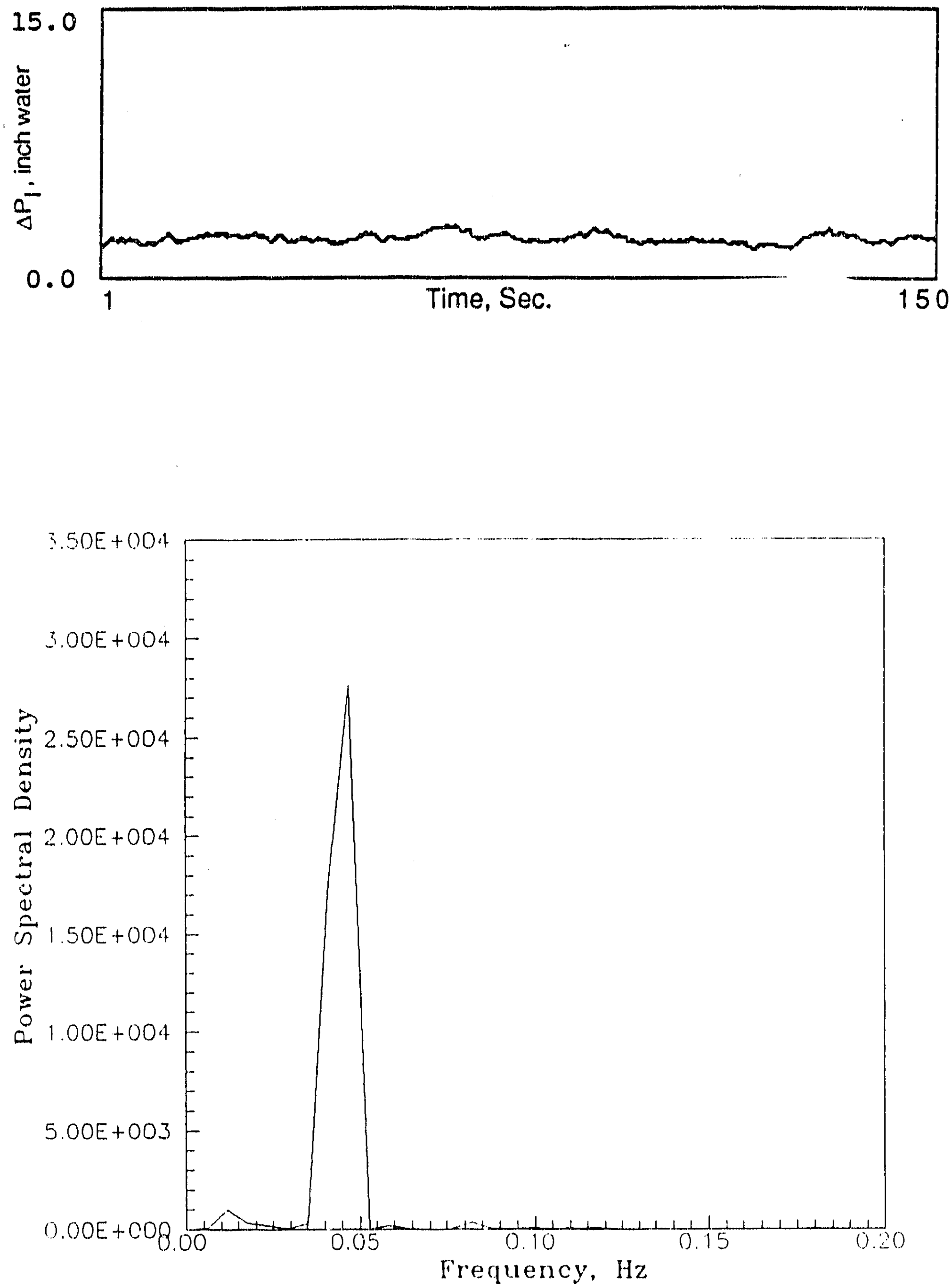


Figure 15. Pressure Oscillations (top), and Corresponding Spectral Density Function (bottom) in the Lower Section [F=20.4 Kg/(m^2.s);U_g=2.89 m/s]

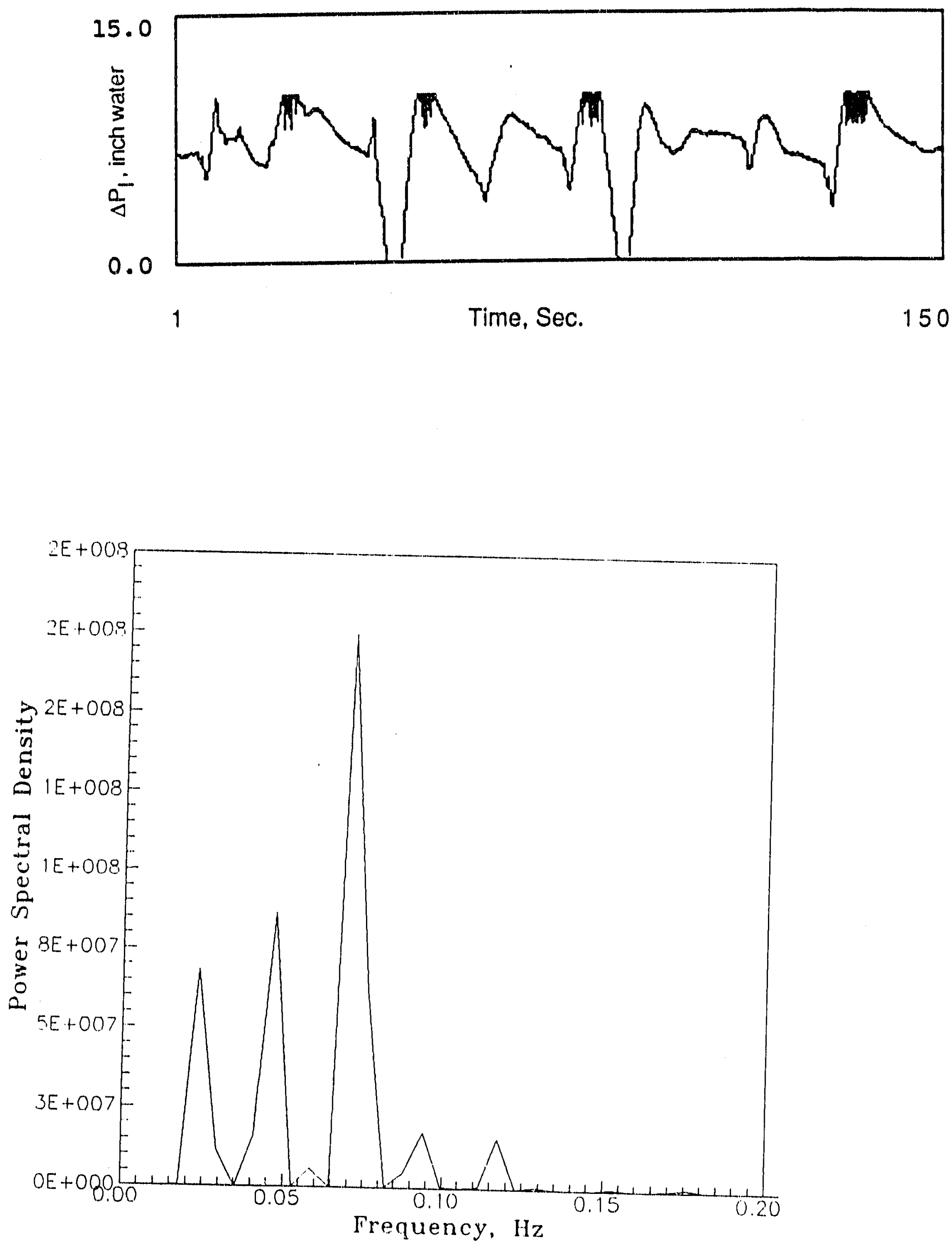


Figure 16. Pressure Oscillations (top), and Corresponding Spectral Density Function (bottom) in the Lower Section [F=32.8 Kg/(m^2.s);U_g=2.89 m/s]

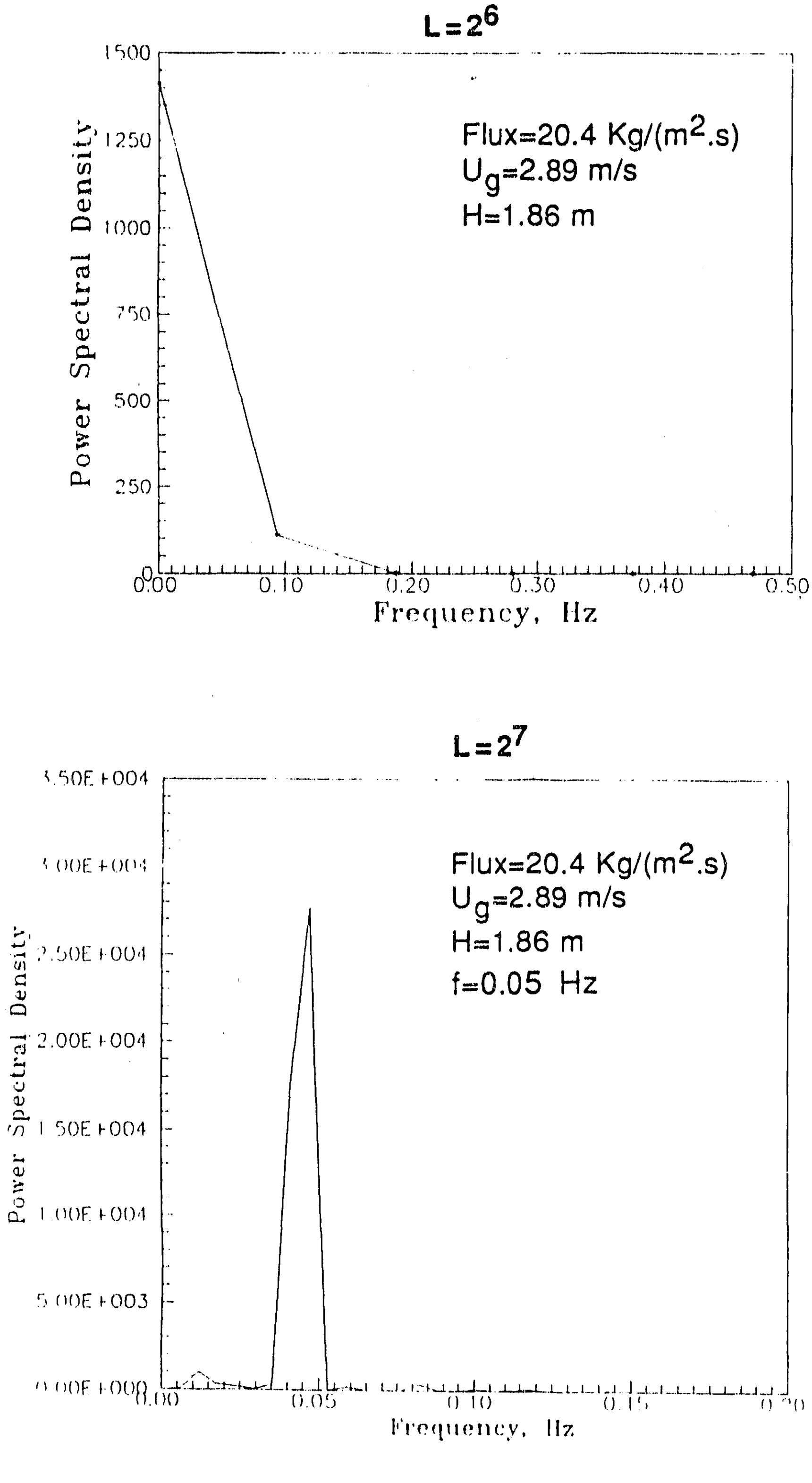


Figure 17. Power Spectrum for $L=2^6$ (top) and $L=2^7$ (bottom)

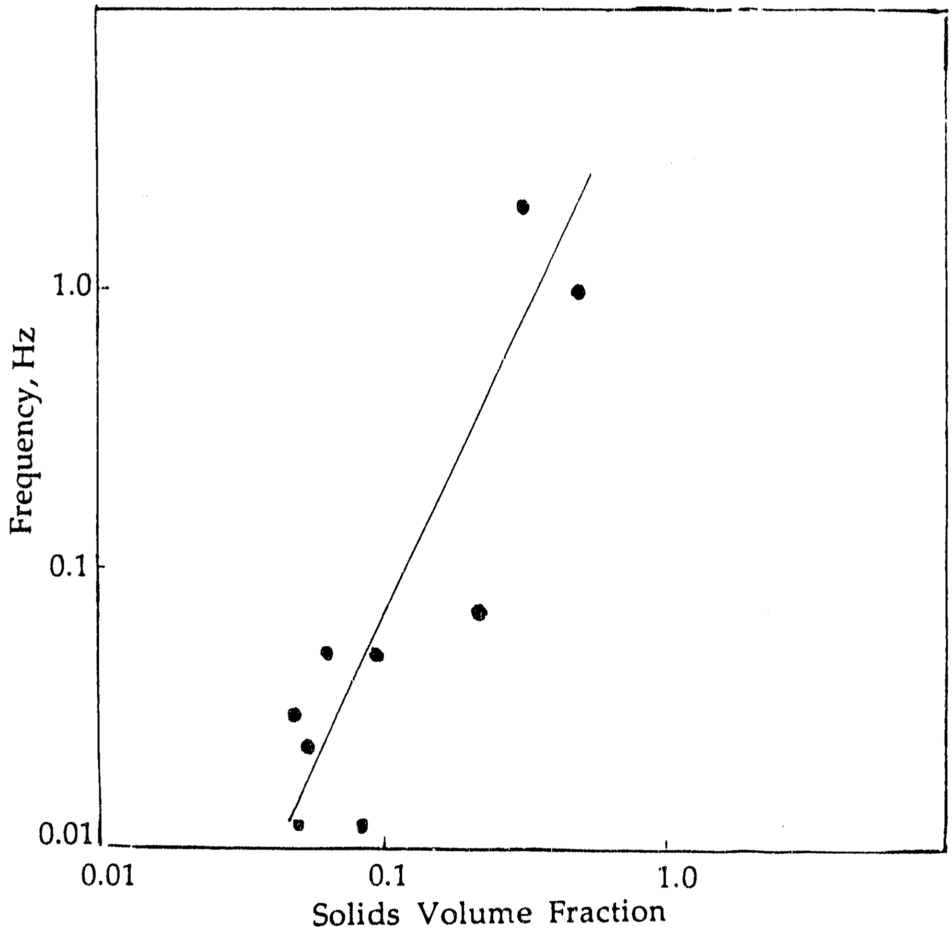


Figure 18. Frequency Vs. Solids Volume Fraction In a Circulating and Bubbling Fluidized Beds

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