MEASUREMENTS OF TURBULENT PRESSURES OF FLOW IN A WATER-CONVEYING PIPE CONTAINING A SIMULATION FUEL BUNDLE

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Abstract

A test apparatus was set up to investigate the turbulent flows and flow induced vibrations in a fluid-conveying pipe containing a CANDU 43-element simulation fuel bundle. The fuel bundle is immersed in test pipe of 4-inch in diameter. A centrifugal pump circulates fresh water with a maximum velocity of 9 m/s at full pump power. The pressure fluctuation near the inner surface of the flow channel was measured at various locations using a pressure transducer and a data acquisition system. It was found that the turbulence away from the test section containing the simulation fuel bundle is largely caused by the pipe flow of high Reynolds number; the turbulence near and inside the bundle structures is the result of pipe flow and fluid-solid interactions. The measurements of pressures near the fuel bundle structure showed that the power spectral density (PSD) of pressure fluctuation has a frequency range of 1-300 Hz, and a normalized maximum pressure range of 0.04 to 0.05 times dynamic pressure. The effects of bundle angular alignments and subchannels on the pressure spectra, Strouhal number range, and streamwise pressure drop are also investigated in this paper. Results presented in this paper are useful in validating the computational models for flow-induced fluid forces that cause the fuel bundle structure to rock and fret.

1. Introduction

Pressure fluctuation is the main source of periodic loads acting on wall surfaces of structures interacting with turbulent flows, and of great importance in a variety of fluid-solid interaction (FSI) studies in nuclear industry. While a lot of research has been done in this area, there are still unanswered questions. The large-scale low-frequency turbulence is responsible for the fluid-solid interaction and is more noted as it represents the frequency range close to the natural frequencies of the solid object. On the other hand, the high-frequency turbulence is also important because it identifies the turbulent kinetic energy transfer rate of the system.

Turbulent wall pressure in pipe flows has been extensively studied in the literature. Clinch [1] measured the pressure spectra in a fairly quiet water tunnel and obtained the relationship between the bulk flow velocity and the root mean square of the turbulent pressures, and also the pressure spectra versus strouhal number. Blake et al. [2] used microphone arrays to

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examine the turbulent boundary layer. Bull [3] presented a thorough review of findings related to both mean square pressure amounts and frequency analysis of turbulent wall pressure. Curling et al [4,5] studied experimentally the turbulent flows in a twelve-rod bundle flow, but in a magnified system. Yang et al. [6] produced valuable turbulent measurements in bundle flow with the focus on turbulent heat transfer.

In this paper, the pressure fluctuation in a 43-element simulation bundle is measured using pressure transducer and data acquisition system. The purpose of the present work is to produce experimental spectral results for bundle flows with a focus on effects of longitudinal locations and Reynolds numbers. The measurements have been produced using the test rig shown in Fig.1. A centrifugal pump circulates water in a piping system. The bundle is immersed in the axial direction of the flow. A miniature pressure transducer is flush-mounted on the inner surface of the pipe. By changing the pump frequency, various flow rates were generated and the corresponding pressure signals and turbulence frequencies were measured. Results presented in this paper are in agreement with those available in the literature for turbulent frequencies.

2. Experimental apparatus

A centrifugal pump and piping system shown in Fig.1 is used to circulate water at different velocities. The mass flow rate of the system is obtained from the pressure differences and pump frequencies using the pump specifications diagrams. The pressure along the piping system is measured using pressure gauges at various locations. The system can be pressurized up to 60 psi, and run at a maximum pump frequency of 30 Hz. Figure. 2 shows the bundle geometry, flow direction, and bearing pads locations on the bundle in different views. A strain gauge type miniature pressure transducer is flush-mounted on the inner surface of the pipe at different locations. The transducer is connected to an IMC CRONOS-PL data acquisition system with a full bridge module. Special care has been taken to ensure that the surface of transducer perfectly flushes with the water flow. The transducer has a sensitivity of 1.1×10^{-5} volt/Pa, and a noise to signal ratio of 2%.

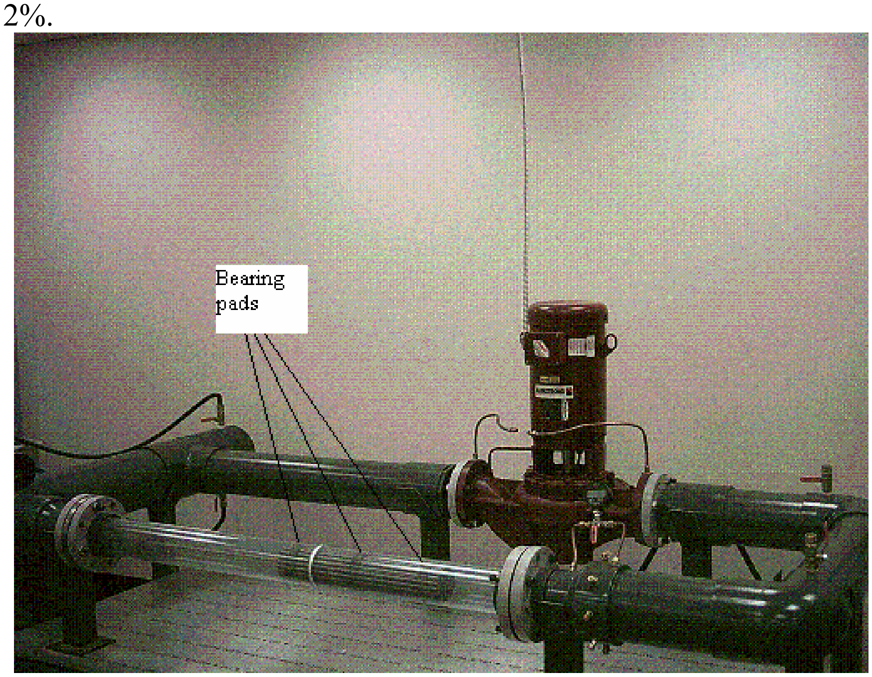

Fig. 1 Test rig: Centrifugal pump, piping system, and the bundle in axial flow

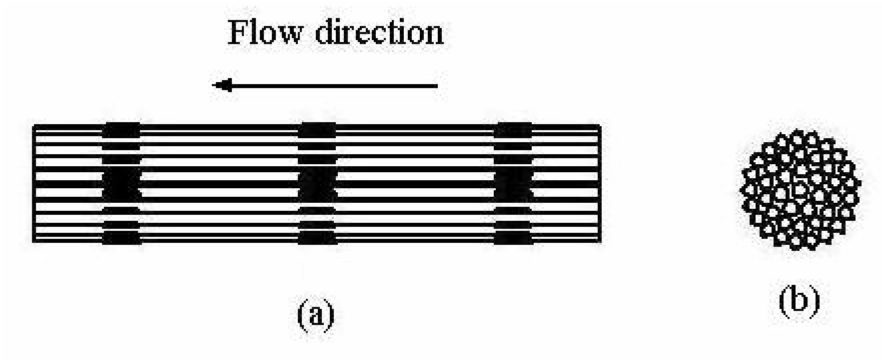

Fig. 2 Bundle geometry: a) Flow direction, and b) Bundle cross-section

3.1 Pipe flow measurements

The wall pressure signal was measured first for the case of pipe flow without bundle, and was compared with the results of Clinch [1] for validation. The flow measurements in a turbulent flow system are subjected to not only the turbulence induced fluctuations, but also the structure-born excitations and acoustic noise of the system. The structure-born excitations are largely caused by the rotational unbalance of the pump blades at a frequency equal to the rotational speed. The acoustic pressure pulsations are caused by the oscillatory pressure at the pump outlet at a frequency equal to the pump rotational speed multiplied by the number of vanes. Proper isolations may be used to reduce structure-born excitations. While affording such a system may demand a large amount of time and expenses, an alternative can be the signal processing. Separation of pipe vibrations [7] and two-point cross correlation [8] by the coherence methods were used to eliminate the unwanted signals forced to the system. In the present work, pressure signals are filtered using a low-pass filter in order to eliminate the effects of structure-born and noise signals. Table.1 shows values of different parameters used in the experiments.

Table. 1 Flow characteristics for different pump frequencies and corresponding flow velocity

f_p (Hz)	U (m/s)	d (m)	Re	Re_τ
12	3	0.1016	3×10^5	1290
17	4.1	0.1016	4.1×10^5	1708
22	5.54	0.1016	5.54×10^5	2239
27	7.01	0.1016	7.01×10^5	2767

Figure. 3 shows the original pressure signal with reference to the mean pressure. The pressure signal has been non-dimensionalized with respect to the dynamic pressure, i.e., $\bar{p} = \dfrac{p}{1/2\rho U^2}$.

The power spectral density of pressure is non-dimensionalized using $\overline{\phi}_p = \dfrac{\phi_p}{\rho^2 U^3 d}$ where ϕ_p is the power spectral density of pressure (mean square per unit bandwidth).

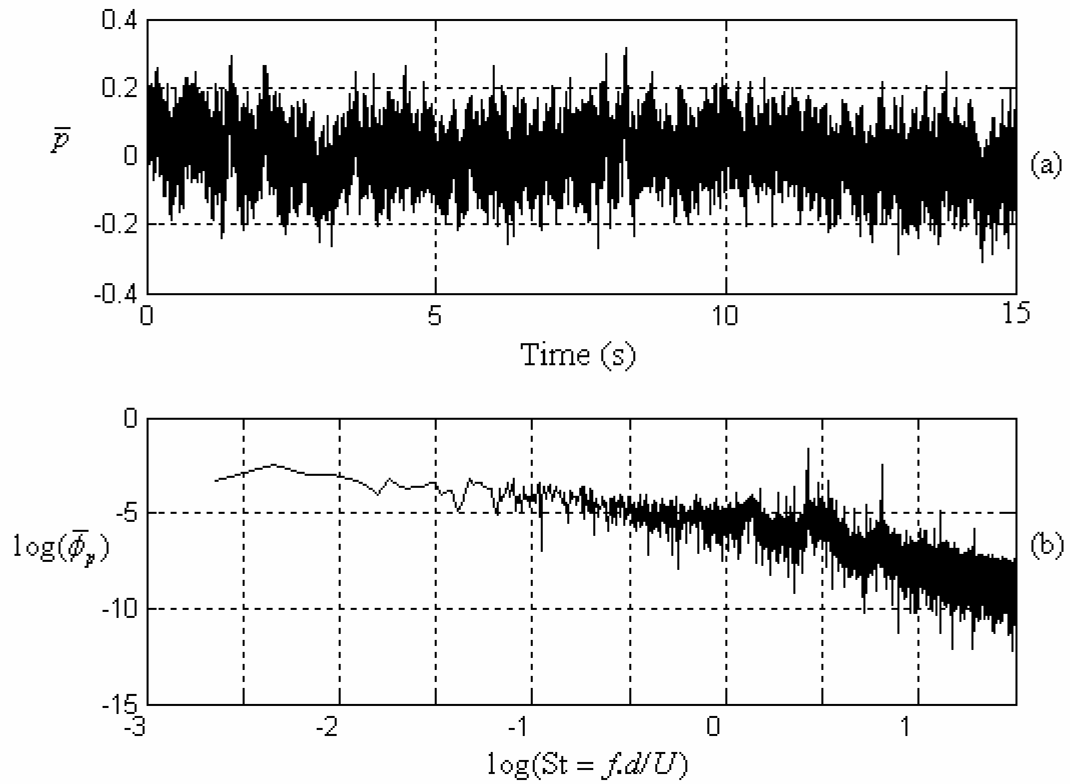

Fig. 3 Wall pressure fluctuations and spectrum in pipe flow: a) Non-dimensionalized pressure fluctuations, normalized by the mean value of pressures versus time, b) Non-dimensionalized power spectral density of pressures versus Strouhal number plotted in a logarithmic scale

The PSD of pressures has been averaged using a quadratic filter and plotted versus Strouhal number in Fig.4 for different Reynolds numbers. Since Strouhal number is used, the plots for different Reynolds numbers are relatively the same. The previous experimental result by Clinch [1] has been used to make comparisons. Figure 5 shows another comparison made about root mean square of pressures for different Reynolds numbers. From both Fig.4, and Fig.5 it is obvious that the present pressure signals are stronger than those previously measured by Clinch [1]. As aforementioned in this report, extraneous low and high frequency noises always affect the signal from different sources such as components of pipe and pump vibrations, and pump acoustics. As a result, the amplitude of the signal is higher than the real pressure signal amplitude. In the next section, the signal is filtered and is focused in the frequency range of interest in order to tackle the problems caused by irrelevant noises. As will be revealed later, by focusing on a low-frequency range a lot of undesirable noises can be filtered out and the pressure signal quality can be improved. This paper focuses mainly on comparisons of bundle flow wall pressure amounts in different longitudinal locations, and using proper filters have proved to be useful to achieve our goals.

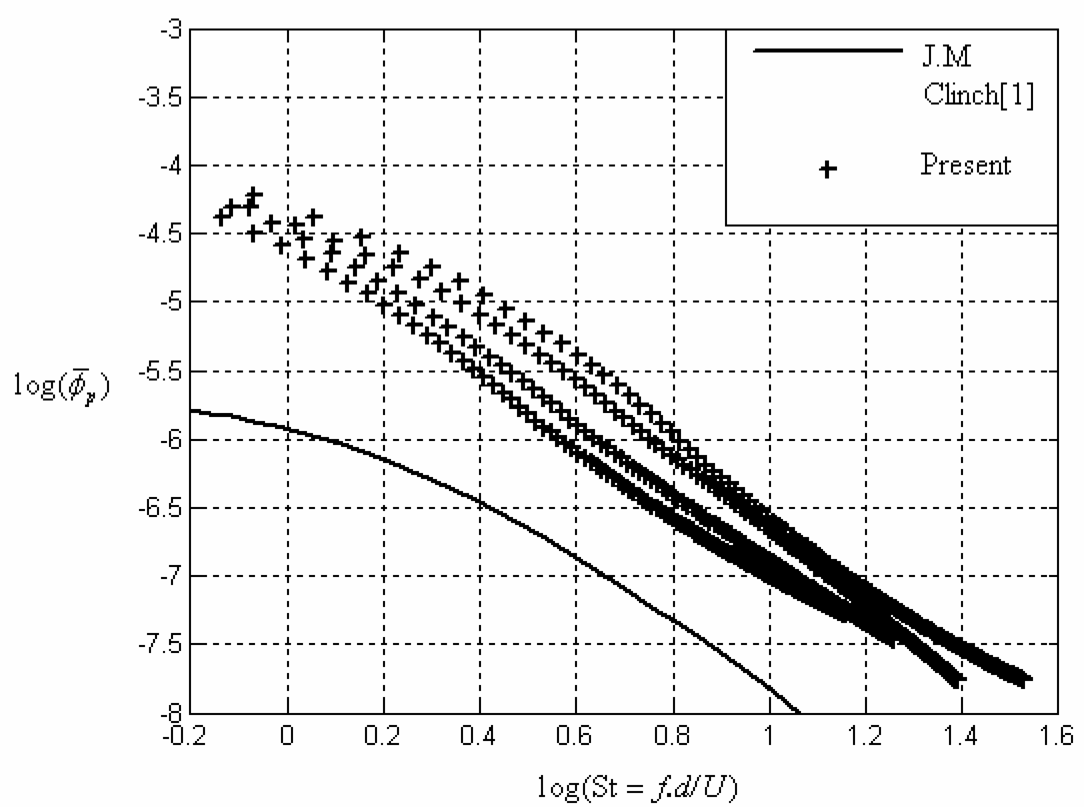

Fig. 4 Comparisons of non-dimensionalized power spectral densities of pressures

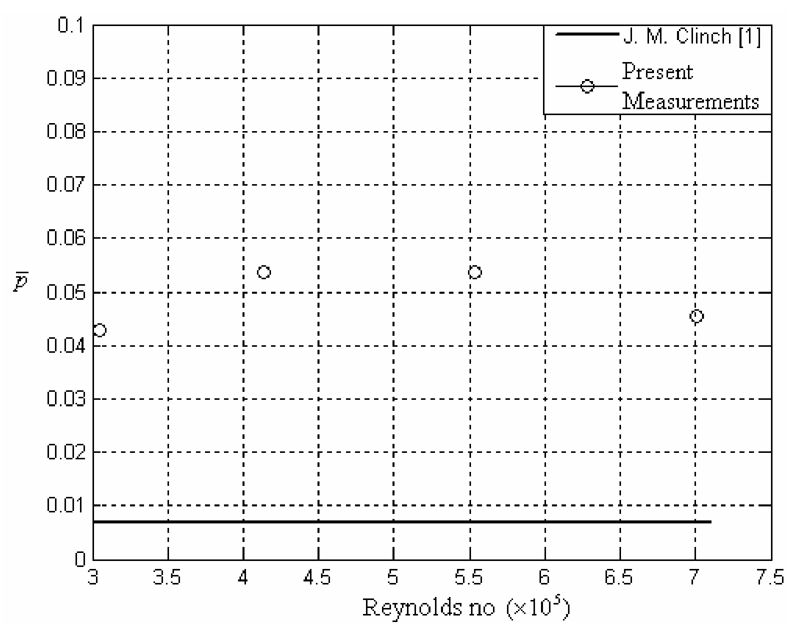

Fig. 5 Ratio of the rms of pressure amounts to the dynamic pressure ($\bar{p} = p / p_d$) at different Re numbers, Comparison between the present measurements and averaged results produced by Clinch [1]

3.2 Filtered pressure signals

While high-frequency turbulence is always important when studying the kinetic energy transfer, lower frequencies are more important from dynamical point of view as they are closer to the dominant frequencies of the structures .i.e. bundles, pipes etc.

Low pass filter can be used to filter out the high frequency large-amplitude signals. The cut-off frequency was obtained after carefully studying the signal and recognizing the extraneous noises and associated frequencies. Abraham et al. [9] used different cut-off frequencies for different Reynolds numbers in a water tunnel. A constant cut-off frequency of 100 Hz is used in this paper to make comparisons that are more sensible over a wide range of flow velocities. Figure.6 shows the pressure fluctuations and PSD after the signal is filtered. From the comparison between Fig.3, and Fig.6 it is obvious that the signal amplitude has been reduced by about 50% and the large-amplitude noise spikes have been removed from the PSD.

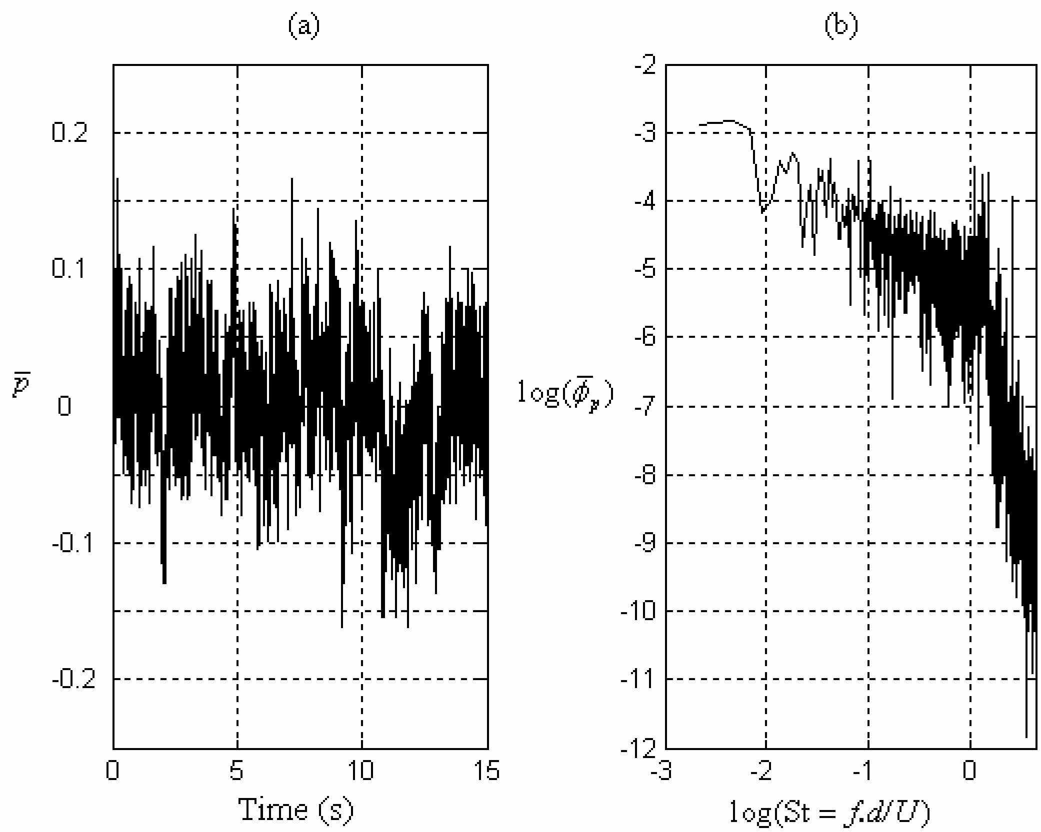

Fig. 6 Filtered pressure signal and spectrum: a) Non-dimensionalized pressure fluctuations normalized by mean value of pressures versus time, b) Non-dimensionalized power spectral density of pressure versus Strouhal number plotted in a logarithmic scale

Figure. 7 shows the non-dimensionalized power spectral density of pressures versus frequency plotted in a logarithmic scale for the four different Reynolds numbers. The effect of noises still has damaged the PSD in the form of peaks, especially in higher Reynolds numbers shown in Fig. 7. The turbulent frequencies seemed to be dependent on Strouhal number as shown in Fig.4. From the results obtained by Clinch [1], others available in literature, and the present report, it is known that the dominant turbulent frequency lies within the range of $0.5<St<1$. The pressure measurements are in agreement with this criterion. The frequencies are shown in Table.2 for different Reynolds numbers.

Table. 2 Turbulent frequencies for different Reynolds numbers in the pipe flow

Reynolds no	3×10^5	4.1×10^5	5.54×10^5	7×10^5
Frequency (Hz)	32.34	36.03	50.44	62.85

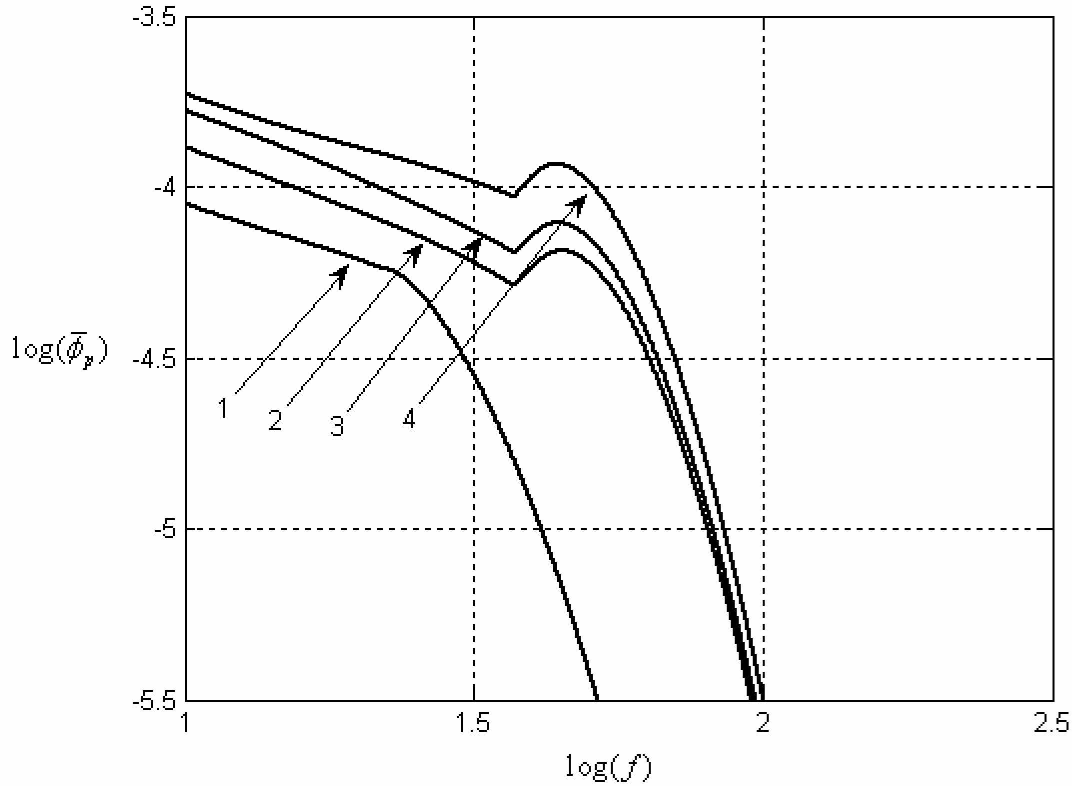

Fig.7 Non-dimensionalized power spectral density of pressure versus frequency in a logarithmic scale: 1) Re $=3\times10^5$, 2) Re $=4.1\times10^5$, 3) Re $=5.54\times10^5$, 4) Re$=7\times10^5$

3.3 Bundle flow measurements

The wall pressure fluctuations in the presence of fuel bundle are measured in this study. The sensor locations and position of the bundle inside the pipe are shown in Fig.8. The longitudinal locations are shown in terms of pipe diameter (*d*). Figure.9 shows the PSD of pressures plotted for one location and different upstream Reynolds numbers. The PSD of pressures in different locations and Reynolds numbers are shown in Fig.10.

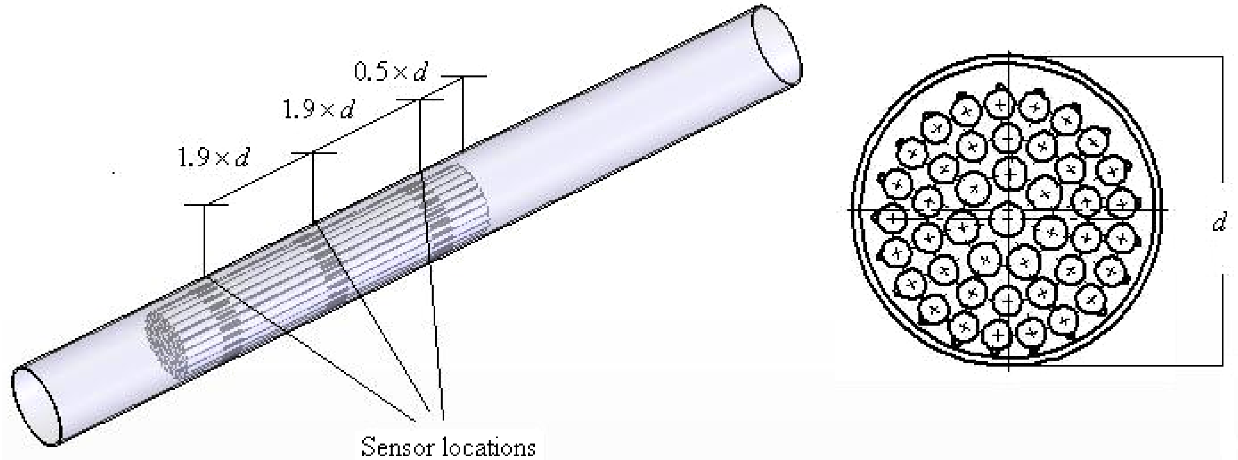

Fig. 8 Bundle position inside the pipe and longitudinal locations of the pressure sensor (left), and cross sectional view of the fuel bundle inside the tube (right)

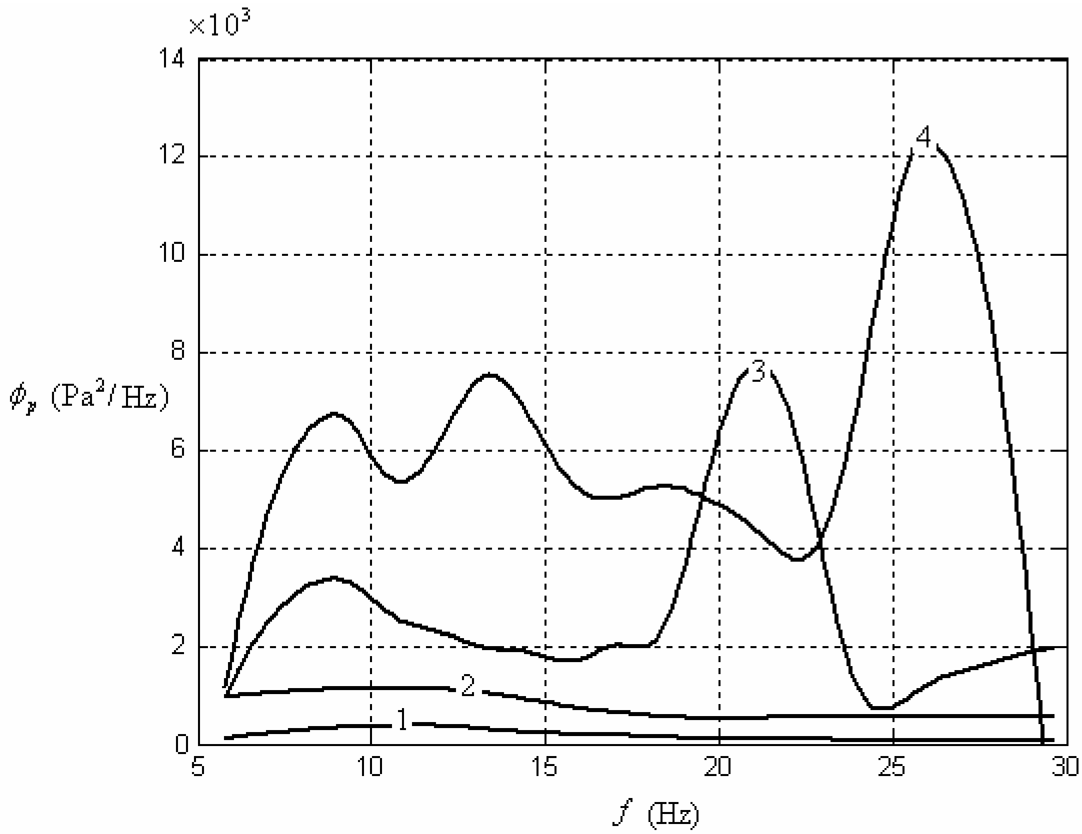

Fig. 9 Averaged PSD of the pressures in bundle flow versus frequency plotted in a linear scale, for different upstream Reynolds numbers: 1) Re $=3\times10^5$, 2) Re $=4.1\times10^5$, 3) Re$=5.54\times10^5$, 4) Re$=7\times10^5$

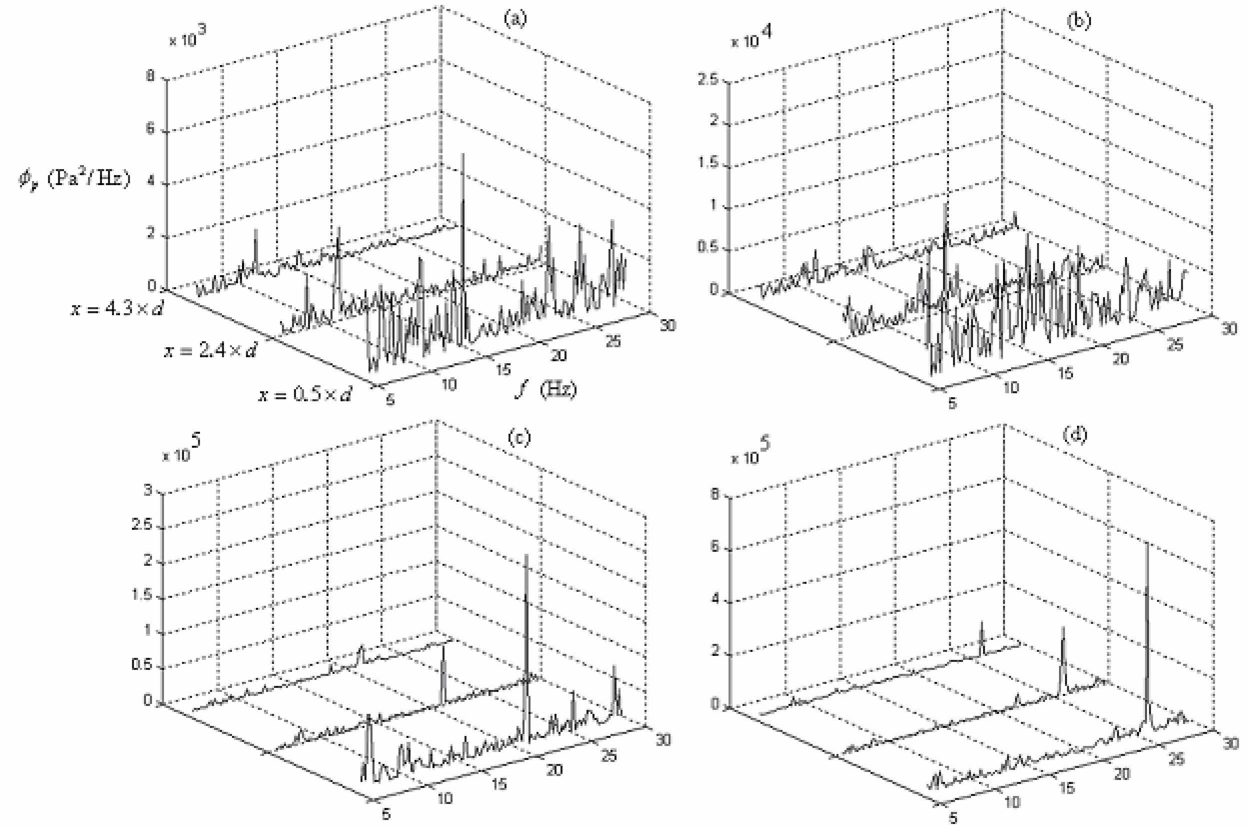

Fig. 10 PSD of pressures for the bundle flow at different longitudinal locations
a) $\mathrm{Re} = 3\times10^5$, b) $\mathrm{Re} = 4.1\times10^5$, c) $\mathrm{Re} = 5.54\times10^5$,
d) Re= 7×10^5

From Fig.9 and comparison with Table. 2, it can be known that the dominant frequencies in the presence of bundle are lower than frequencies in the case of pipe flow at the same upstream Reynolds numbers. While low-frequency signal still affected the PSD, dominant frequencies are definitely recognizable in the averaged PSD and follow the expected pattern i.e. increase with fellow velocity or Reynolds number as PSD amplitudes do. In Fig. 10, PSDs are plotted for different Reynolds numbers and different longitudinal locations as illustrated in Fig.8. As shown in Fig. 10, the PSD amplitude is decaying with axial distance. This phenomenon is better pronounced in higher Reynolds numbers. Curling et al [4] reported same behavior, but in the same paper, they reported a reverse pattern in other circumpherential locations and showed that turbulence development depends on the gap size and energy transfer rate, and consequently the PSD amplitudes can increase or decrease with axial distance depending on the circumpherential position. The dominant pattern in the present experiment is what has been shown in Fig. 10 apparently because of the presence of numerous subchannels in the simulation bundle.

4. Conclusions

Turbulent pressure fluctuations beneath the turbulent boundary layer on the wall surface of a pipe have been measured and analyzed in this paper. The pipe flow measurements were conducted to make comparisons with the available data in literature and validate the experimental procedure. Once the validity was obtained, the measurements were taken in the presence of a 43-element simulation bundle.

Pipe and pump vibrations and the acoustic noise generate large-amplitude extraneous noises. Normally, special measures such as use of sound absorbers and suspension systems are taken to provide a quiet structural-born-vibration-free system. In this paper, low-frequency digital filters were used instead to tackle the problem. However, the measured signal amplitude still is higher than the expected value although the measured turbulent frequency is in agreement with the Strouhal range given in the literature. By adding the bundle, the turbulence was somehow damped and the dominant frequencies decreased compared with the case of pipe flow without bundle at same upstream Reynolds numbers. The main finding of this study is the pattern shown in Fig 10, where a decrease in PSD amplitude is observed in the longitudinal direction. This phenomenon was also reported in [4] but was ruled out when the experiment was repeated in different azimuthal directions showing that the turbulence development depends on the gap size and azimuthal location. Although fairly same results were obtained in the present experiment, the pattern shown in Fig. 10 was observed in most of the azimuthal locations.

5. Nomenclature

d = Pipe diameter (m)

U = Centerline flow velocity (m/s)

ρ = Density (Kg/m^3)

p = Pressure (Pa)

$p_d = 1/2\rho U^2$ = Dynamic pressure (Pa)

$\overline{p} = p / p_d$ = Non-dimensionalized pressure

ϕ_p = Power Spectral Density of pressures (Pa^2/Hz)

$\overline{\phi}_p = \dfrac{\phi_p}{\rho^2 U^3 d}$ = Non-dimensionalized Power Spectral Density of pressures

f = Turbulence frequency (Hz)

f_p = Pump blades passing frequency (Hz)

Re = Reynolds number

Re_τ = Reynolds number based on the friction velocity

St = $f.d$/U= Strouhal number

6. References

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