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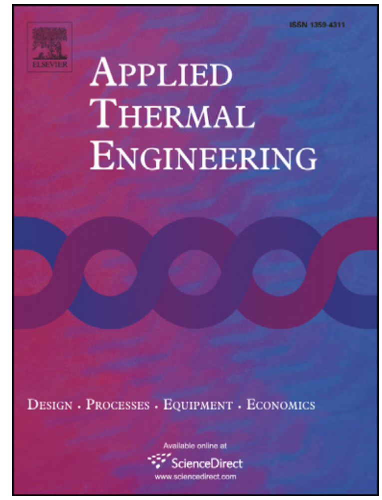

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Analysis of Pressure Fluctuations in a Natural Gas Engine Under Lean Burn Conditions

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Abstract

We have investigated the cycle-to-cycle pressure fluctuations in a natural gas engine under lean burn conditions. In particular, we have examined the dynamics of the indicated mean effective pressure (IMEP) variations for four different values of the equivalence ratio. For each equivalence ratio, we used a continuous wavelet transform to identify the dominant spectral modes and the number of cycles over which these modes may persist. Our results reveal that when the mixture is not so lean, the IMEP undergoes persistent low frequency oscillations together with high frequency intermittent fluctuations. For leaner mixtures, the low frequency periodicities tend to be less significant, but high frequency intermittent oscillations continue to be present. When the mixture is made sufficiently lean, high-frequency oscillations become persistent, together with weak low frequency variations reflecting weak combustion. These results may be useful for understanding the long-term variability of the pressure fluctuations. They can also be used to develop effective control strategies for improving the performance of natural gas-fired engines under lean burn conditions.

Keywords: natural gas engine, pressure fluctuations, lean burn conditions, wavelet analysis

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1. Introduction

In view of the fact that combustion under lean burn conditions leads to improved fuel efficiency, there has been a great deal of interest in lean burn technology for natural gas engines [1]. A lean mixture has a higher resistance to knock than a stoichiometric mixture, and thus allows higher compression ratios to be used. A natural gas engine with a high compression ratio can attain high thermal efficiency due to low combustion temperatures and low throttling losses [2]. If, however, a very lean mixture is used, it may cause misfire and result in increased exhaust emissions and reduced efficiency due to unstable combustion [3]. Instabilities may be due to cycle-to-cycle fluctuations in combustion variables such as the in-cylinder pressure. In addition to the equivalence ratio of the fresh combustible mixture, the in-cylinder pressure fluctuations are influenced by other factors such as the composition of the burned gases supplied to the cylinder, and engine aerodynamics. The dynamics of cycle-to-cycle pressure variations can be quite complex and evolve on multiple timescales. In order to develop effective control strategies for efficient combustion, it is important to understand the dynamics of cycle-to-cycle pressure variations [4-6]. Earlier studies on pressure fluctuations were carried out primarily in gasoline and diesel engines [7-18]. Using the methods of nonlinear dynamics and other techniques, researchers have investigated the complex dynamics of pressure fluctuations in these engines, including the possibility of chaotic oscillations [10-16]. The dynamics of pressure variations in natural gas-fired engines have also been analyzed by similar methods [19-23].

In our recent work, we have used wavelet analysis to investigate the cycle-to-cycle variability of pressure oscillations in spark-ignition [17] and diesel [18] engines under different loading. In this paper, we perform wavelet analysis of cycle-to-cycle pressure variations in a natural gas-fired engine under different lean burn conditions. In particular, we examine the cyclic fluctuations in indicated mean effective pressure (IMEP) for four values of the equivalence ratio: φ = 0.781, 0.677, 0.595 and 0.588. We explore the possibilities of periodic and intermittent patterns of fluctuations as the equivalence ratio is changed from lean to very lean conditions..

It is well known that Fourier analysis can be used effectively to detect the dominant periodicities in a time series in terms of spectral peaks. However, a Fourier analysis is unable to determine the time intervals over which the periodicities may persist. Furthermore, it cannot identify if the time series under consideration exhibits temporal intermittency. Wavelet analysis, on the other hand, is capable of detecting the dominant spectral modes and their duration as well as intermittency.

The traditional Fourier transform uses a fixed size window for the entire time series and thus loses the temporal information. A windowed Fourier transform also known as a Short-time Fourier transform (STFT) circumvents this limitation by applying the Fourier transform on a short segment of the signal at a time using a fixed-size window and then sliding the window in time. The temporal variations of the periodicities, if any, can thus be determined. However, because a fixed-size window is used in STFT, the frequency resolution as well as the time resolution is fixed. As a consequence, for a given signal either the frequency resolution may be poor or the time localization may be less precise, depending on the size of the chosen window. In contrast, using variable-size windows, wavelet analysis provides an elegant way of adjusting the time and frequency resolutions in an adaptive fashion. A wavelet transform uses a window that narrows when focusing on small-scale or high frequency features of the signal and widens on large-scale or low frequency features, analogous to a zoom lens [24]. Wavelet analysis has been used for time series analysis in a wide variety of applications.

Our presentation is organized as follows. First, we briefly describe the experimental set up which was used to measure the in-cylinder pressure. From the pressure measurements, the indicated mean effective pressure (IMEP) is calculated and used in our analysis. This is followed by a review of the wavelet analysis methodology. Next we present and discuss the application of wavelet analysis to the IMEP time series to reveal the dynamics of IMEP fluctuations. Finally, a few concluding remarks are given.

2. Experimental Set up

For the present purpose, the pressure measurements were carried out in a turbocharged, six-cylinder, four-stroke diesel engine equipped with an intercooler. The engine was adapted for use with natural gas by adding a multi-point port fuel injection system and spark plugs. A compression ratio of 10.5:1 was used for the experiment. A photograph of the experimental stand is shown in Figure 1. Further details of the engine configuration may be found in [20]. The power output of the engine was measured by an eddy current dynamometer and the engine speed was recorded with a magnetic pickup. The pressure inside the cylinder was measured using a Kistler 6125B quartz pressure transducer which was connected to a Kistler 5015A charge amplifier. The pressure transducer was mounted in one of the six cylinders of the engine. The position of the crankshaft was monitored by an encoder which was rigidly mounted on the engine. Experiments were performed in the Department of Mechanical, Electronic and Control Engineering at Beijing Jiaotong University, China. The reader is referred to [23] for further details. As mentioned in the introduction, we analyzed the cycle-to-cycle variations of the indicated mean effective pressure (IMEP). IMEP is defined as the constant equivalent pressure which acting on the piston during the expansion stroke performs the same amount of work as the variable pressure in the cylinder. From the in-cylinder pressure measurements, IMEP can be calculated using the formula: IMEP = L_i / V_s, where L_i is the amount of work indicated in the cylinder, and V_s is the volume of piston displacement. The work L_i is estimated by integrating the measured pressure [25].

3. Wavelet Analysis Methodology

A wavelet is a small wave with zero mean and finite energy. The continuous wavelet transform (CWT) of a signal with respect to a wavelet is given by the convolution of the signal with a scaled and translated version of the wavelet. Consider a time series $\{x_i\}$ with i = 1, 2, 3, …, N. The CWT of this time series with respect to a wavelet $\psi(t)$ is defined by [26]:

$$W_n(s) = \sum_{n'=1}^{N} \left(\frac{\delta t}{s}\right)^{1/2} x_{n'} \psi^* \left[\frac{(n'-n)\delta t}{s}\right]. \qquad (1)$$

Here n is the time index, s is the wavelet scale, and δt is the sampling interval. The wavelet $\psi(t)$ is referred to as the mother wavelet, and an asterisk on ψ denotes its complex conjugate. The scale parameter controls the dilation ($s > 1$) and contraction ($s < 1$) of the mother wavelet. The amount of signal energy contained at a specific scale s and location n is defined as the wavelet power spectrum (WPS), and is given by the squared modulus of the CWT: $|W_n(s)|^2$. This power spectrum which depends on both scale and time is represented by a surface. By taking contours of this surface and plotting them on a plane, a time-scale representation of the wavelet power spectrum can be derived. A time-scale representation is found to be useful for extracting important features of signals arising in many applications. An alternate representation, namely, a time-frequency representation has also been used. A scale-to-frequency conversion, which follows a reciprocal relationship, can be easily made by use of the formula: $f = f_0 f_* / s$, where f is the instantaneous frequency of the signal, f_* is the sampling frequency, and f_0 is the center frequency of the mother wavelet (see below). In our analysis we used a complex Morlet wavelet as the mother wavelet. A complex Morlet wavelet consists of a plane wave modulated by a Gaussian function and is described by [26]:

$$\psi(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2}. \qquad (2)$$

Here $\omega_0 = 2\pi f_0$ is the order of the wavelet, with f_0 being the center frequency. The value of ω_0 controls the number of oscillations in the mother wavelet and thus determines the frequency and time resolutions of the corresponding CWT. A larger value of ω_0 provides a higher frequency resolution; a smaller value of ω_0, on the other hand, leads to a higher time resolution. In our computations we have used a Morlet wavelet of order 6 as the mother wavelet. This choice provides a good balance between time and frequency localizations. For this choice, the scale is also approximately equal to the Fourier period and thus the terms scale and period can be used interchangeably for interpreting the results.

4. Results and Discussion

The IMEP time series for the four equivalence ratios considered here, namely, φ = 0.781, 0.677, 0.595 and 0.588 are plotted in panels (a), (b), (c) and (d), respectively, in Figure 2. It can be readily seen that the amplitude of the cycle-to-cycle pressure fluctuations increases with decreasing values of φ, i.e., as the fuel-air mixture becomes increasingly lean. Note that a different vertical scale has been used in Fig. 2a than in Figs. 2b-d, in order to display the fluctuations in a magnified fashion. We now discuss the results of wavelet analysis of the IMEP time series.

The wavelet power spectra (WPS) of the IMEP time series shown in Figure 2 are depicted in Figure 3. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. The cross-hatched region below the thin U-shaped curve denotes the cone of influence (COI), where zero padding has reduced the variance. Results with the COI may be unreliable and should be used with caution. The black contours represent the 90% confidence level, with respect to a red-noise (autoregressive lag1) background spectrum [26]

It is seen from Figure 3(a), which applies for φ = 0.781, that there is strong power in a band around the 35-cycle period and this band persists continuously over 90 cycles from cycle numbers 127 to 217, approximately. In other words, the IMEP fluctuations in this band complete more than two oscillations. In addition, this figure shows the presence of high-frequency intermittent fluctuations in the 2-6 cycle band. Next we consider Figure 3(b) which corresponds to a leaner mixture with φ = 0.677. Here we observe strong power around the 65-cycle periodic band persisting approximately over 90 cycles from cycle numbers 120 to 210. Clearly, this periodic band completes less than two full oscillations. As in Figure 3(a), Figure 3(b) shows the presence of high-frequency intermittent fluctuations. Intermittency is also observed in the low frequency band of around the 12-cycle period. A few other low frequency periodicities are seen in this figure; however, these periodicities do not persist long enough to be considered true oscillations. The results for the equivalence ratio of 0.595 are depicted in Figure 3(c). As in Figure 3(b), short-term intermittent fluctuations are also seen in this figure. Furthermore, the figure shows a few weaker low frequency features which because of their short duration cannot be considered true oscillations. Finally, we consider the leanest mixture with an equivalence ratio φ = 0.588. The corresponding wavelet power spectrum is illustrated in Figure 3(d). Note that this figure indicates persistent high frequency oscillations of IMEP. From Figure 2(d), we can see that this effect is associated with alternating high and low values of the pressure fluctuations in successive cycles. Such a small value of equivalence ratio may lead to incomplete combustion in a given cycle. In the next cycle, however, the residual fuel will be added to the fresh fuel-air mixture making the combustion process more efficient. This alternating sequence of combustion events may be responsible for persistent high frequency behavior of the IMEP fluctuations as seen in the wavelet power spectrum in Figure 3(d). This figure also shows a few very weak low frequency periodicities reflecting weak combustion.

The above results may be summarized as follows. When the mixture is not so lean, the IMEP undergoes persistent low frequency oscillations together with high frequency intermittent fluctuations. For leaner mixtures, the low frequency periodicities tend to be less significant, but high frequency intermittent oscillations continue to be present. When the mixture is made sufficiently lean, high-frequency oscillations become persistent, together with weak low frequency variations.

5. Concluding Remarks

We have analyzed the cycle-to-cycle fluctuations of indicated mean effective pressure (IMEP) in a natural gas-fired engine under lean burn conditions. Four different values of the equivalence ratio were examined. Using a continuous wavelet transform, it was shown that depending on the equivalence ratio, the IMEP may undergo low frequency persistent oscillations and/or high frequency intermittent fluctuations.

We have demonstrated the usefulness of wavelet analysis for characterizing the cyclic pressure fluctuations. Wavelet analysis provides valuable information about the various periodicities and their duration as well as intermittency. This information may be important to understand the long-term variability of IMEP. Such information may also be utilized to develop effective control strategies for efficient combustion in natural gas-fired engines, thereby improving fuel economy with optimum emission control.

The implications of the results for engine operation would be to minimize the high-frequency oscillations which may lead to misfires and simultaneously reduce fuel consumption. This means a compromise between the stoichiometric and lean combustion limits. In order to describe the optimal conditions, more systematic studies must be performed taking into account the fuel consumption. We shall report such analysis in a future publication.

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Figure captions

Figure 1. The experimental set up of the natural gas-fired engine.

Figure 2.Time series of the indicated mean effective pressure (IMEP) for the four equivalence ratios considered here: (a) φ = 0.781, (b) φ = 0.677, (c) φ = 0.595 and (d) φ = 0.588.

Figure 3. Wavelet power spectra of the IMEP time series shown in Figure 2. The panels (a)-(d) correspond to the time series (a)-(d), respectively in Figure 2. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. The cross-hatched region is the cone of influence, where zero padding has reduced the variance. Black contour is the 90% confidence level, using a red-noise (autoregressive lag1) background spectrum.

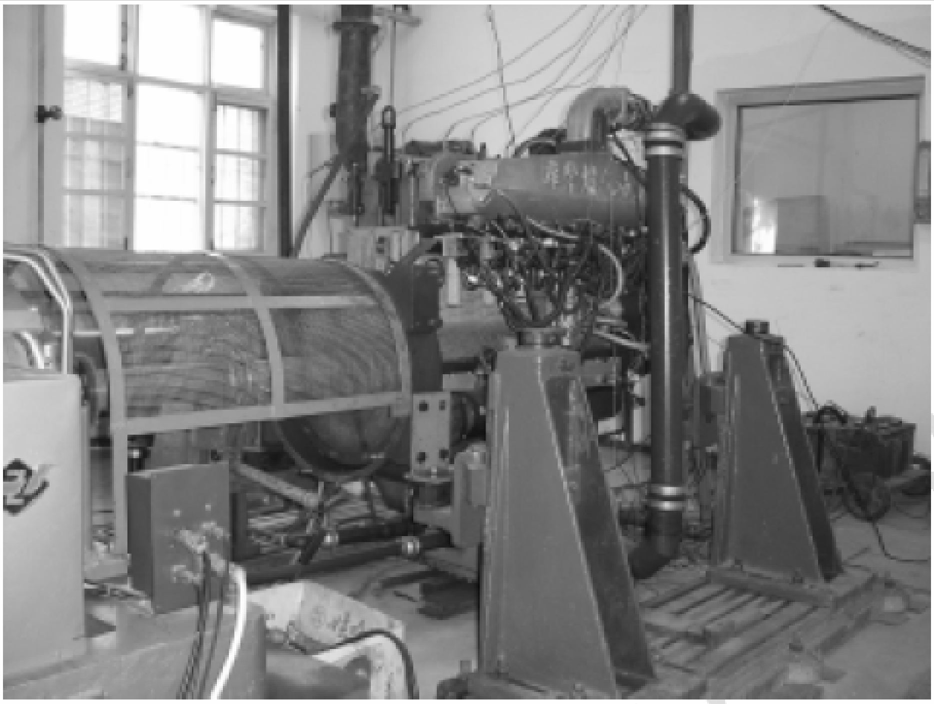

Figure 1

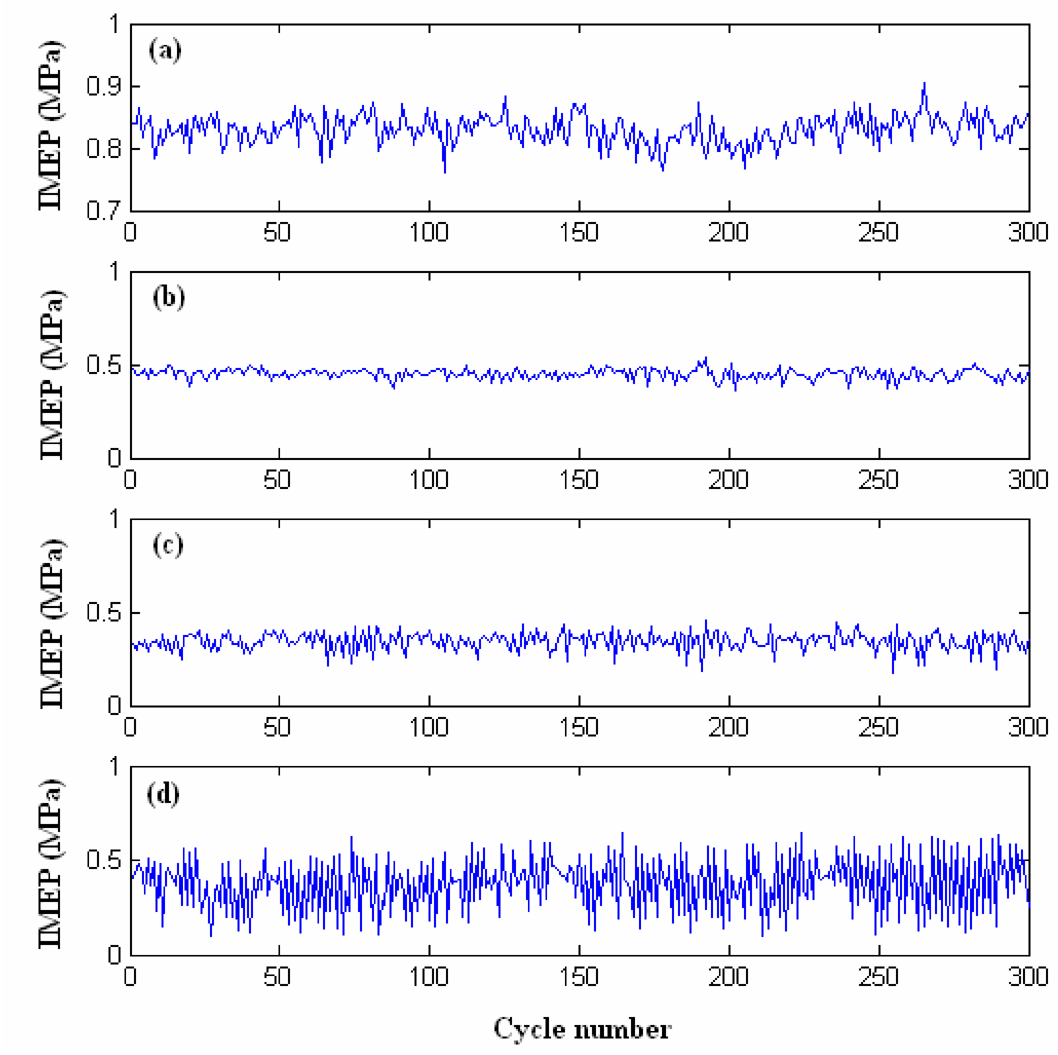
(a)
(b)
(c)
(d)
IMEP (MPa)
IMEP (MPa)
IMEP (MPa)
IMEP (MPa)
1
0.9
0.8
0.7
0.5
0
0
50
100
150
200
250
300
Cycle number

Figure 2

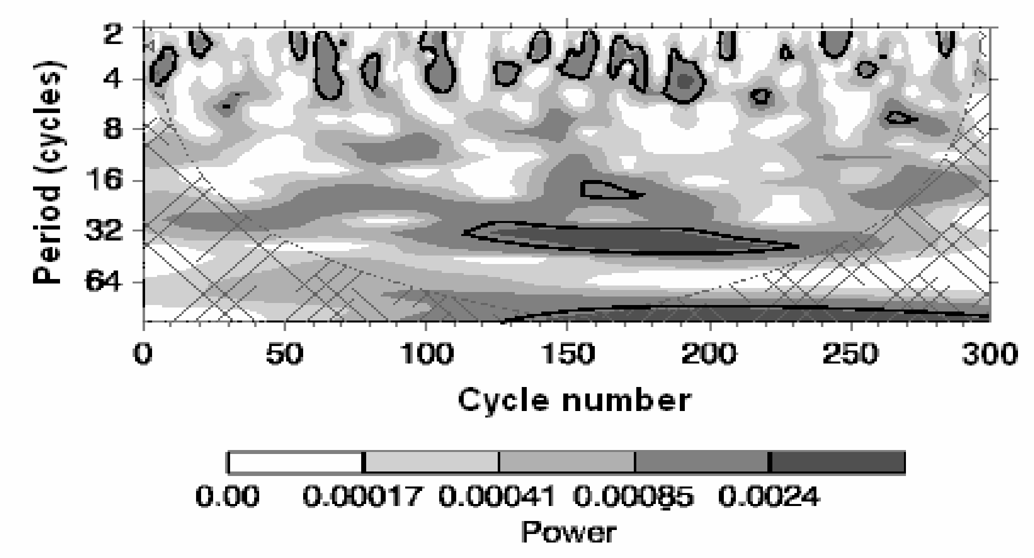

Figure 3(a)

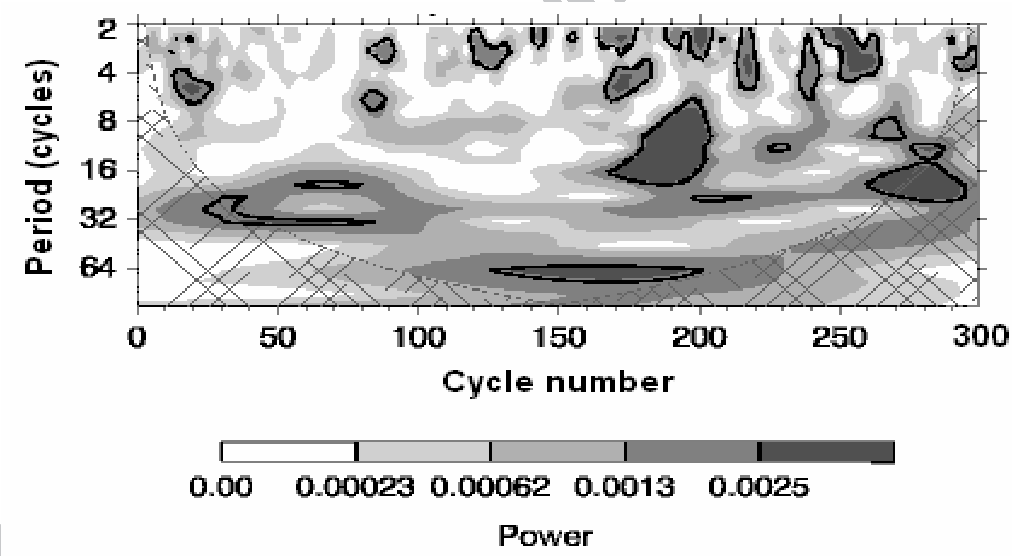

Figure 3(b)

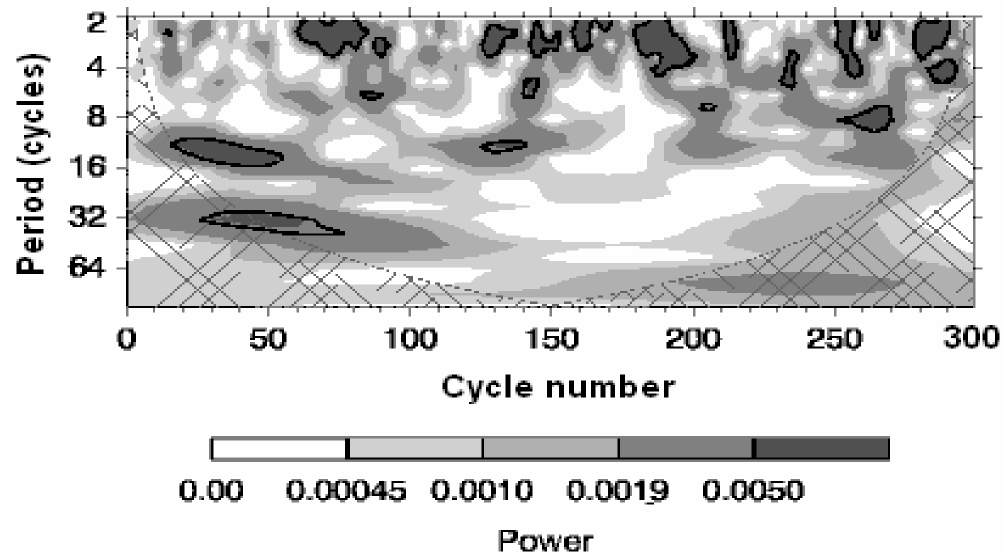

Figure 3(c)

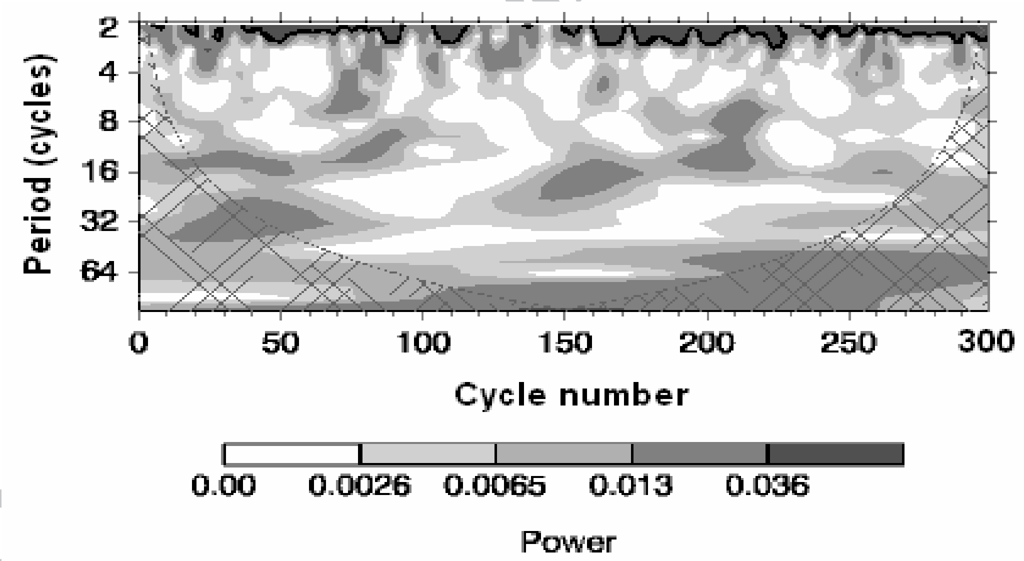

Figure 3(d)