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Analysis of cyclic variations in a diesel engine using Wavelets: A Review

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***Abstract:*-- The combustion process of internal combustion (IC) engines show variations from one cycle to another even if the speed, load and all other engine parameters are kept constant. These variations and disturbances in engine combustion parameters are called cyclic variations. There are different methods for analyzing cyclic variations like coefficient of variation (COV) method, correlation coefficient, wavelet transform, artificial neural network etc. Indicated mean effective pressure, heat release rate, pressure rise rate and maximum cylinder pressure are the different combustion parameters whose cyclic variability is analyzed. Wavelet transform method is very effective technique for analyzing cyclic variations in combustion parameters of diesel engine. It can simultaneously give information about the magnitude as well as the locations of cyclic variations in a diesel engine.**

Index Terms:- Wavelets, Diesel Engine, Cyclic variations, Cyclic fluctuations.

I. INTRODUCTION

A wavelet is a function with zero mean and finite energy. Wavelets are time-localized wave like oscillations. The wavelet's amplitude begins to increase from zero and returns to its initial state after a brief amount of time. Wavelet Transform is the mathematical approach that can split a signal into numerous low resolution levels by changing the shifting and scaling parameters of the mother wavelet function. The wavelet transform method can provide insight into the temporal and spectral features of time series data simultaneously. Wavelets transform method is used to calculate magnitude and periodicities of cycle to cycle variations in internal combustion engines. In STFT method only sinusoidal functions are used while in wavelet transform method various types of functions are used. Functions in wavelet transform are selected based on the aim and application of analysis. In this study Morlet function is used for analyzing cyclic variations. It is a complex function which is very well suited for analyzing oscillatory data [1]–[3]. The Morlet function is represented by the following equation-:.

$$\varphi(t) = \frac{1}{\pi^{\frac{1}{4}}} e^{i2\pi f_o t} e^{\frac{-t^2}{2}}$$

The Continuous wavelet transform (CWT), Global wavelet spectrum (GWS) and Wavelet power spectrum (WPS) are the tools used for analyzing cyclic variations in combustion variables in IC engines. The CWT of the function x(t) with reference to a wavelet w(t) is the convolution of function x(t) with translated and scaled version of w(t). The wavelet w(t) is known as mother wavelet. Convolution is a mathematical concept in which a third function is generated using two given functions. Wavelet power spectrum is the square modulus of continuous wavelet spectrum and it is also called as scalogram. The WPS is dependent on both time and scale and a scale-time representation of the WPS may be constructed

by taking contours and projecting them on a plane. Visual inspection of a scale-time representation can reveal the different periodicities and intermittency. In WPS x-axis denotes the cycle number while y-axis denotes the periodicities of time series. Colors of wavelet power spectrum give information about the energy of signal. Red colour represents highest energy while blue colour denotes lowest energy of signal. The region of WPS at which edge effects become prominent is known as the Cone of Influence. The area within the cone of influence is taken into account, whereas the area outside of it is ignored [1].

The time average of wavelet power spectrum is called global wavelet spectrum. The peak of GWS gives information about the periodicity in the time series. In Global wavelet spectrum x-axis represents power while y-axis denotes the period. Periodicities in time series are denoted by the spikes in GWS. Detailed explanation about CWT, WPS and GWS is available in next section of this work [1], [4].

II. METHODOLOGY AND MATHEMATICAL EQUATIONS

The indicated mean effective pressure can be thought of as the pressure acting on the piston over full stroke which would give the same work output as given by the actual cycle". IMEP is the performance characteristics used for the comparison of output and design of various engines regardless of their sizes. IMEP was calculated using the below mentioned formula.

$$IMEP = \frac{W_{ind}}{V_d}$$

Where W_{ind} represents indicated work and V_d represents displacement volume. Coefficient of variation and standard deviation used to calculate cyclic variability is given by the following equations.

$$COV(X) = \frac{SD(X)}{\overline{X}} \times 100\%$$

$$SD(X) = \sqrt{\frac{\sum(X - \overline{X})^2}{Nc}}$$

Here X is the main parameter, COV(X) denotes coefficient of variation, SD(X) denotes standard deviation, $\overline{X}$ denotes mean of the data and Nc denotes number of cycles.

In order to analyze the strength and periodicities of cyclic variations using wavelet transform method a mother wavelet function is to be selected. In this study Morlet wavelet function is selected as the mother wavelet. The equation and other details of Morlet wavelet function were discussed in chapter 1 on this work. Continuous wavelet transform is calculated using the below mentioned expression.

$$CWT_n\,(a) = \left(\frac{\delta t}{a}\right)^{\frac{1}{2}} \sum_{n=0}^{N-1} x'_n\, \Psi^* \left[\frac{(n' - n)\delta t}{a}\right]$$

Where Ψ(t) is the mother wavelet function, Ψ^* represents conjugate of mother function, n denotes localised time index, parameter "a" denotes the scale factor and x_n represents the time series data.

The Wavelet Power Spectrum gives indication about the alterations of variances at various frequencies or scales. Wavelet power spectrum is the square modulus of continuous wavelet spectrum and it is also called as scalogram. It shows the signal energy magnitude at a certain scale (a) and at a given location (n).WPS is calculated by the below mentioned formula.

$$WPS = |CWT_n(a)|^2$$

The normalised WPS is given by the below mentioned equation. σ denotes the standard deviation in the normalised WPS equation.

$$WPS_n = \frac{|CWT_n(a)|^2}{\sigma^2}$$

In WPS cycle number is represented at X-axis. Y-axis represents periods and colour plot represents the intensity of fluctuations. There is a colour bar in WPS curve which is log at the base two of WPS i.e. $\log_2$ (WPS) which means if value on colour bar is -3 then this means WPS is $2^{-3} = 1/8$. WPS can be used to assess the fluctuations of variance and its occurrence frequency in time series data of combustion characteristics. The region of WPS at which edge effects become prominent is known as the Cone of Influence. The area within the cone of influence is taken into account, whereas the area outside of it is ignored [4].

Time average of wavelet power spectrum is called as global wavelet spectrum. The spike position in global wavelet spectrum gives information about presiding periodicities in the time series data. The GWS is calculated by the below mentioned formula. In Global wavelet spectrum X-axis represents power while Y-axis denotes the periods.

$$GWS = \frac{1}{N} \sum_{n=1}^{N} |CWT_n(a)|^2$$

A MATLAB code is generally developed to calculate Continuous wavelet transform of IMEP data using Morlet function as the mother wavelet. GWS and WPS of IMEP data at all the tested loads were plotted using the MATLAB program.

III. WAVELET ANALYSIS OF CYCLIC VARIATIONS

There are various methods for analyzing cyclic variations in combustion characteristics of diesel engine. Wavelet analysis is another mathematical concept that can give detailed analysis of cyclic variations in combustion variables of CI engines. In the frequency-time domain, the wavelet transform can simultaneously represent functions and show their local properties**.** Some of the previous researches on analyzing cyclic variations in combustion parameters of diesel engine through wavelet transform method are listed below-:

Zhijia Yang et al. [5] investigated the source of cyclic variations in combustion characteristics of a diesel engine. Study was only focused on the determining the source of cyclic variations within the injection system of fuel. Statistical analysis and factor analysis were the two methods used for studying combustion variability of CI engines. It was found that fluctuations in common rail fuel pressure and fluctuations in injector current were the two main sources of cyclic variability in diesel engines. It was observed that cyclic variations can be minimized by using Fuel path feedback technique. It was suggested that correct knowledge of combustion stability and source of variations in combustion parameters are very essential for formulating efficient control strategies of diesel engine.

R.K. Maurya et al. [6] experimentally investigated the impact of cycle to cycle variations in CI engine using wavelets. Cyclic variations of IMEP and Total heat released were analysed by Morlet wavelet transform method. Experiment was performed at different compression ratios and various engine loads at the constant engine speed of 1500rpm. Highest global wavelet spectrum power was observed at low load and low compression ratios in both the parameters thus indicated about high cyclic variability at low load conditions. GWS power decreased on increasing the load thus indicated that cyclic variations decreased on increasing the load. Maximum intensity cyclic fluctuations of total heat released were scattered over large number of cycles while maximum intensity cyclic fluctuations of IMEP were scattered in smaller number of cycles.

R.K. Maurya and Neekanti Akhil [7] investigated the impact of compression ratio, engine load and injection pressure on cycle to cycle variations in a CI engine using wavelets. The experiment was performed at a fixed engine speed and different loads at three different injection pressure and compression ratios. Cyclic variations reduced on increasing the compression ratio at fixed load. Maximum peak power of GWS for Pmax, Total heat release and IMEP were observed at compression ratio of 16:1 at no load condition in the periodic range of 221 to 625 cycles. At partial and high loads GWS peak is almost same for all the compression ratios while period of occurrence of GWS peak were different. Minimum cycle to cycle variations were observed at injection pressure of 200bar. It was observed that drivability of CI engine vehicle is mostly affected by the cyclic variations of indicated mean effective pressure and the emissions characteristics of diesel engine is mostly affected by the cyclic variations of total heat release.

Asok K. Sen et al. [8] analyzed cyclic variations of mean indicated pressure in a diesel engine using wavelet analysis. Many short, long and intermediate periodicities were observed in pressure data using WPS plot. It was noticed that intermediate and long periodicities in pressure data were dependent on the load of the engine. It was observed that cyclic variations of mean indicated pressure were influenced by variations in the engine speed. Maximum cyclic variations were observed at the engine speed of 1200rpm and 2000rpm. It was found that the cyclic variations in diesel engine are highly influenced by the fuel composition and fuel injection rate.

IV. CONCLUSION

Statistical method gives information about the temporal fluctuations available in the given data. Statistical method does not give information about the spectral characteristics present in the given data. Statistical method provides the information about the magnitude of variations but does not give information about the periodicities of variations in the given data. Wavelet transform is an effective technique for analyzing non stationary signals in several frequencies and time domains simultaneously. The wavelet transform method can provide insight into the temporal and spectral features of time series data simultaneously. Wavelet transform method is used to determine the periodicities as well as magnitude of cyclic variations in IC engines.

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