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Approximate Analyasis of SI Engine Knocking Using Wavelet and its Control with Cooled Exhaust Gas Recirculation

Engine knocking acts as an obstruction for improving the engine performance, hence limiting the compression ratio below the highest usable compression ratio (HUCR). Even though the design condition is kept much below HUCR, knocking occurs during the long-running conditions due to the reduction in the heat carrying capacity of the coolant. The present study focuses on the prediction of knocking from the acoustic signals produced by the engine using Wavelet theory. Thermodynamic modelling of the spark ignition engine is done to analyse the performance enhancement that could be achieved by increasing the amount of cooled exhaust gas recirculation (EGR). During the occurrence of knocking, cooled exhaust gas is recirculated to control the in-cylinder temperature and hence the knocking. In addition to the reduction in temperature, the analysis shows that the thermal efficiency of the engine has increased about 12% with the cooled EGR.

Keywords: *Spark Ignition Engine, Thermodynamic Modelling, Auto-ignition, Knocking, Wavelet, Cooled Exhaust Gas Recirculation.*

1. INTRODUCTION

Nowadays, a lot of researches are done for improving the engine performance. The performance of SI engine is found to improve with the increase in compression ratio [1]. However, with the increase in compression ratio, in-cylinder temperature also gets increased, which results in engine knocking [2]. Hence, knocking acts as a barrier for further increase in the compression ratio from highest usable compression ratio (HUCR). The occurrence of knocking can be reduced by decreasing the in-cylinder temperature, which could be achieved by using inter-cooler or exhaust gas recirculation (EGR) system. The thermal efficiency can also be increased to a certain extent with the fraction of exhaust gas recirculated, in addition to the reduction in in-cylinder temperature [3]. EGR can be used as an effective tool in controlling the occurrence of engine knocking on the real-time basis, which is the primary concern in our work.

Real-time control over knocking could be achieved only if its occurrence can be predicted effectively. Many models have been developed for the prediction of knocking based on the fuel equivalence ratios, cylinder pressure, temperature, fuel octane number and ignition timing [4 – 7]. These models cannot be used effectively on real-time basis due to complexities of the model and lack of accuracy to predict in the entire range of engine operating conditions. Hence, the parameters that are affected by the occurrence of knocking is chosen. Initially, the pressure fluctuations inside the cylinder during the combustion process were used to determine the occurrence of knocking. Later, Ollivier et al. [8] employed Nanofluids as the coolant and found that the transient temperature is varying with the occurrence of knock. He has amplified the transient temperature fluctuations by providing grooves in the cylinder liner, facing the coolant flow [8]. These transient fluctuations can be sensed to predict the occurrence of knocking.

In this work, knocking is identified from the sound waves produced by the engine using Wavelet transform. The frequency of the knocking sound is supposed to fall in the high-frequency range between 5 kHz and 20 kHz [9]. Any change that occurs in this high-frequency range from that of the base sound wave is inferred to as due to the occurrence of knock. The fundamental frequency of the sound wave depends upon the engine speed. The energy obtained to fundamental frequencies and its harmonics during the engine operating conditions is compared with that of the normal engine operating conditions at same engine speed. Any harmonics of the fundamental frequency obtaining higher energy than in the normal case also predicts the occurrence of knocking. EGR is used to control the in-cylinder temperature and thereby avoiding the occurrence of knocking. Once knocking is detected, the electronic control unit is used to control the amount of EGR in accordance with the intensity of knocking. With the amount of EGR, due to the lack of sufficient amount of fresh air for the complete combustion, the in-cylinder pressure also gets decreased in addition to the in-cylinder temperature [3]. This results in the reduction in power, even though the thermal efficiency of the cycle is improved to a certain extent [3].

Details of the technique used for the prediction and control of knocking is discussed in the following sections.

Received: May 2015, Accepted: July 2015
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doi:10.5937/fmet1601022J

2. ACOUSTIC SIGNAL PROCESSING AND SYSTEM CONTROL

Figure 1. shows the block diagram representation of various processes associated with the signal analysis and knock control. The sound signal produced by the engine is recorded by means of a microphone, which is amplified and passed through the analog to digital converter (ADC). This processed signal is analysed in the MATLAB environment to extract its features.

The major problem associated with recorded sound is the interference of noise. The sounds from other parts of the vehicle, nearby vehicles, horn etc. are few examples of unwanted sound that will be present in the recorded sound signal, and is called noise. Before analysing the recorded signal, this unwanted sound (noise) needs to be eliminated from the sound signal for getting better results. This could be achieved by applying signal filtering techniques. In this work, the background noise is eliminated by a signal de-noising algorithm, which will be explained in the coming section. During normal engine operating conditions, the fundamental frequency of the sound produced by the engine will be varying only up to 400 Hz [9]. This fundamental frequency can be used to find the speed at which the engine is running. The amplitude of fundamental frequency and its harmonics also provides a wide guess about the occurrence of knocking, which combined with the data's in the high-frequency range (above 5 kHz) confirms it. For finding the fundamental frequency and its harmonics, the wavelet transform is used.

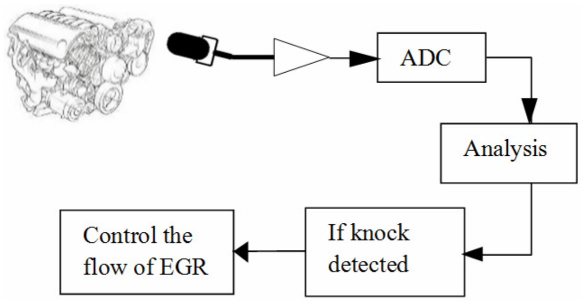

Figure 1. Schematic diagram of various processes used for the detection and control of engine knocking using the acoustic signal processing technique.

2.1 Wavelet theory

A wavelet is a mathematical function which divides a continuous-time signal into different components. Li et al. [10] proposed an audio de-noising algorithm based on adaptive wavelet soft threshold in order to progress the effect of the content-based songs retrieval system. Adaptive wavelet soft threshold is based on the gain factor of the linear filter system in the wavelet domain and the wavelet coefficients Teager energy operator [10]. Wavelets are used in various fields including physics, medicine, biology and statistics. The principal advantage of wavelet transform over Fourier transform is that Wavelets are localized in both frequency and time whereas the Fourier transform is localised in frequency only. Short-Time Fourier Transform (STFT) is something similar to that of Wavelet transform. The wavelet transform is developed as an alternative way to overcome the problems associated with STFT, in which it provides uniform time resolution for all frequencies [13]. In the wavelet analysis, a mother wavelet (ψ) is adopted. The family of wavelets are generated by dilating and translating ψ, and is given by [14],

$$\psi^{a,b}(x)=|a|^{-\frac{1}{2}}\psi\left(\frac{x-b}{a}\right). \tag{1}$$

Where $a,b\in R, a\neq 0$. The normalization has been chosen so that $\left\|\psi^{a,\beta}\right\|=\|\psi\|$ for all a, b and the continuous wavelet transform with respect to this wavelet family is obtained as [14],

$$\left(T^{wave}f\right)(a,b)=\langle f,\psi\rangle=\int dx\, f(x)|a|^{-\frac{1}{2}}\overline{\psi\left(\frac{x-b}{a}\right)} \tag{2}$$

The wavelet analysis is the breaking up of the signal into scaled and shifted version of the original signal [12]. The wavelet transforms are classified into two groups: Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). Both CWT and DWT are continuous-time (analog) transforms and can represent continuous-time (analog) signals.

There are several wavelet families in the wavelet analysis. In this work, the Daubechies wavelet family is used. The Daubechies wavelet family is denoted as dbN, where N is the order of wavelet. The 9th order Daubechies is selected, since the wavelet function of db9, is similar to the sound signal to be analysed.

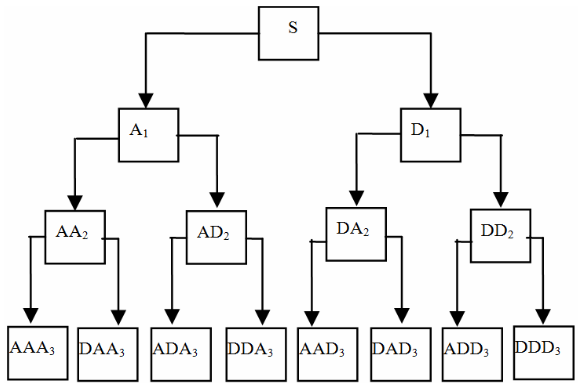

Figure 2. Wavelet decomposition tree

For filtering the sound signal for eliminating the noise using wavelet filters, the signal sequence needs to be decomposed. Wavelet packet decomposition, which is a wavelet transform where the sampled signal is passed through more filters than DWT used for it. In wavelet packet decomposition, a signal is split into high-pass components (approximation) and low-pass component (details) known as wavelet decomposition tree [11]. The wavelet decomposition tree is shown in figure 2. S is the original signal while A and D represent approximations and details respectively. The decomposition is achieved by successive high-pass filtering and low-pass filtering of the time domain signal, which is defined as [15],

$$y_{high}[k]=\sum_{n}x(n)\cdot g(2k-n) \tag{3}$$

$$y_{low}[k]=\sum_{n}x(n)\cdot h(2k-n) \tag{4}$$

2.2 Acoustic analysis and control

Various processes are used for analysing the sound waves. In this work, the sound wave is read using the MATLAB environment and is decomposed by wavelet packets at a level of 7 using db9. The decomposition is an iterative process in which the signal is broken into several lower resolution components. The number of levels denotes the level of the iteration step. After decomposition, the signal is de-noised by using a wavelet packet. Finally, the Power Spectral Density (PSD) of the de-noised signal is obtained for the purpose of further analysis.

Since the knocking sound is supposed to fall in the high-frequency range, this region is chosen for the analysis. Since the characteristics of the sound produced depend upon the engine speed, the database is created for various engine speeds during normal combustion. This database is used to compare with the PSD of the sound wave at every instant of engine operation. Any deviation in PSD from that of the database for the same engine speed is treated as due to the occurrence of knocking. Whenever the knock is detected, a relay circuit is used to open the valve of the EGR system to circulate the cooled exhaust gas back into the engine along with the fresh charge, thus reducing the in-cylinder temperature and hence the engine knock.

3. THERMODYNAMIC MODELLING OF EGR SYSTEM

The control volume considered for the analysis is limited to the combustion chamber and small portion of the inlet and exhaust ports. During intake and exhaust strokes, the system is considered to be open while during compression and expansion it is a closed system.

The thermodynamic relations for temperature and pressure for all process, with the expection of the combustion process is obtained as [1],

$$\frac{dT}{dt} = \frac{1}{\left(m_u, c_{p,u} + m_b c_{p,b}\right)}\Big[\dot{Q}_u + \dot{Q}_b + \dot{m}_{in} h_{in} - \dot{m}_b h_b - P\frac{dV}{dt}\Big] \tag{5}$$

$$\dot{m} = \frac{n_v c_p A_T p_1}{\sqrt{RT_1}}\left(\frac{p_2}{p_1}\right)^{1/\gamma}\left\{\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} \tag{6}$$

The value of each term in (5) and (6) depends upon the type of process that the engine is undergoing.

During the combustion process, the zone is divided into two parts, burned and unburned zones and the thermodynamic relations are obtained as [1] according to the following formulas:

$$\frac{dT_u}{dt} = \frac{1}{m_u c_{p,u}}\left[\dot{Q}_u - P\frac{dV_u}{dt}\right] \tag{7}$$

$$\frac{dT_b}{dt} = \frac{1}{m_u c_{p,u}}\left[\dot{Q}_b + \dot{m}_b\left(h_u - h_b\right) - P\frac{dV_b}{dt}\right] \tag{8}$$

$$\frac{dP}{dt} = \left[P\left(\frac{\dot{m}_u}{\rho_u} + \frac{\dot{m}_b}{\rho_b} - \frac{dV}{dt}\right) + \frac{R_u}{c_{p,u}}\left(\dot{Q}_u - P\frac{dV_u}{dt}\right) + \left(\dot{Q}_b + \dot{m}_b\left(h_u - h_b\right) - P\frac{dV_b}{dt}\right)\frac{R_b}{c_{p,b}}\right]\frac{1}{V} \tag{9}$$

Initial values for T_u and P is obtained from equation (5) and (6) while the initial value for T_b is taken as the adiabatic flame temperature for the given equivalence ratio [1]. Various terms coming in the above equations are discussed in the following sections.

3.1 Heat transfer

The heat transfer coefficient varies due to the complex gas flow inside the cylinder, with piston position and time [2]. Heat transfer coefficient is used to calculate the heat transfer across the system. Heat transfer correlation found by Hohenberg is [16],

$$h_g = 130V^{-0.06}P^{0.8}T^{-0.4}\left(1.4 + \overline{S_p}\right)^{0.8} \tag{10}$$

3.2 Gas flow rates

The mass flow rate of gas through poppet valve is described for a compressible flow as follows [17],

$$\dot{m} = \frac{n_v c_p A_T p_1}{\sqrt{RT_1}}\left(\frac{p_2}{p_1}\right)^{1/\gamma}\left\{\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} \tag{11}$$

a. Mass fraction burned

Double-Wiebe function used to find the mass fraction burned during the combustion process takes into consideration about the slower burning rate at the combustion chamber walls also and is defined as [18],

$$x_b = \left(1-\alpha_{wall}\right)\left\{1-\exp\left(-\alpha\left(\frac{\theta-\theta_0}{\Delta\theta}\right)^{m+1}\right)\right\} + \alpha_{wall}\left\{1-\exp\left(-\alpha\left(\frac{\theta-\theta_0}{\Delta\theta}\right)^{m+1}\right)\right\} \tag{12}$$

4. RESULTS AND DISCUSSION

4.1 Acoustic analysis

The sound produced by Yamaha FZ bike's engine and ambassador’s diesel engine is recorded for the analysis. After decomposing the recorded sound signal in the MATLAB environment, the noise present in the signal is eliminated using the wavelet filter db9. The result obtained after de-noising the recorded sound signal of Yamaha FZ bike along with the original signal is shown in figure 3. The original signal shows an irregular pattern due to the presence of noise while the de-noised signal shows a regular pattern of a smooth signal.

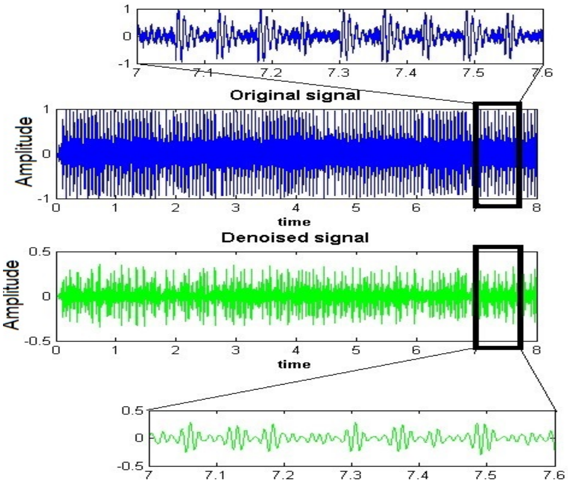

Figure 3. The time domain of the original and denoised sound signal produced by the four stroke single cylinder engine of Yamaha FZ rotating at 3950 rpm.

The power spectral density of the de-noised signals is obtained using the wavelet packets. The results show that there are many peaks in the power spectrum obtained. The frequency value corresponding to the first peak is known as fundamental frequency and the rest of the peaks shows its harmonics. The fundamental frequency of an engine depends on the engine speed, or on the number of firings, hence it is also known as firing frequency. In figures 4 and 5, it can be seen that the fundamental frequency of the engine is varying with the engine speed. From the figure 4 (A), for a single cylinder four stroke engine of Yamaha FZ, the fundamental frequency 29.02 Hz denotes that 29.02 firings in one second will occur. Since it is a four stroke engine, there will be two rotations before each firing, thus the engine speed can be calculated as 29.02 x 2 x 60 = 3482.4 rpm. While recording the sound, the tachometer reading had shown 3500 rpm. Slight variations occurred due to the fluctuation of the engine speed.

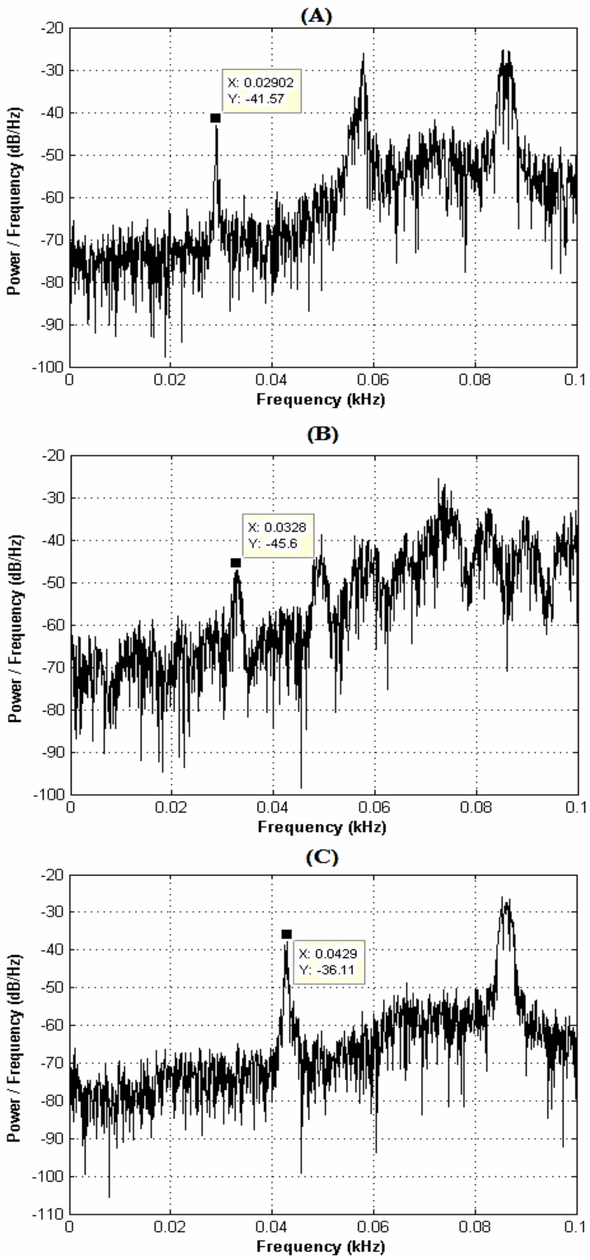

Figure 4. Power Spectral Density of the sound signal produced by four stroke single cylinder engine of Yamaha FZ rotating at (A) 3500 rpm, (B) 3950 rpm, (C) 5150 rpm.

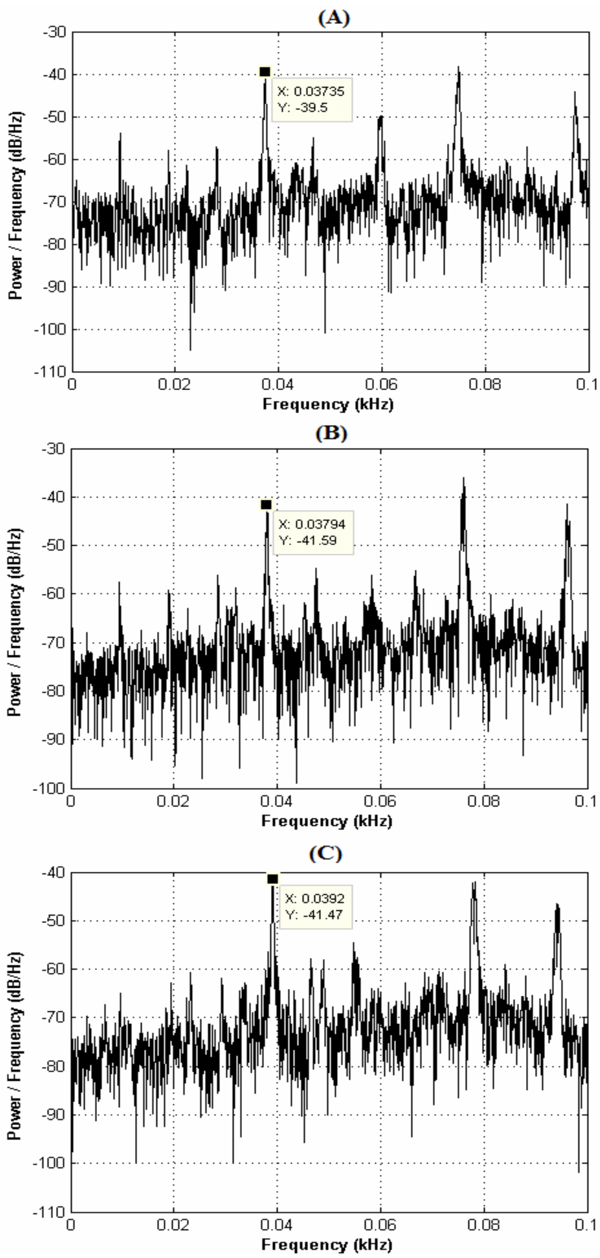

Figure 5. Power Spectral Density of the sound signal produced by four stroke four cylinder diesel engine of Ambassador rotating at (A) 1120 rpm, (B) 1140 rpm, (C) 1180 rpm.

For the ambassador engine, since it is a four cylinder four stroke engine, there will be two firings in every engine rotation. Therefore, half the value of fundamental frequency provides its engine revolutions per second. From the figure 5 (A). for a fundamental frequency 37.35 Hz, the engine speed can be calculated as 37.35 x 30 = 1120.5 rpm. This shows only a slight variation from the tachometer reading, which is 1120 rpm, which is due to the less fluctuation of speed in the diesel engine. From these results, it is clear that the fundamental frequency of the engine depends upon the engine speed. During the occurrence of knocking, the energy level of fundamental frequency or its harmonics changes in addition to the occurrence of higher energy level in the high-frequency range. For identifying the occurrence of knocking, these changes needs to the analysed. Since the fundamental frequency changes with the engine speed, a database is to be made for the entire range of engine speed during normal combustion conditions. These can be compared with that of the real-time values of the sound signal produced by the engine during running conditions. Any deviations from the database value can be inferred as due to the occurrence of knocking.

4.2 Exhaust gas recirculation

The effect of EGR on the in-cylinder temperature is as shown in figure 6. The temperature is found to be decreasing with the increase in the amount of cooled EGR. This is due to the reduction in the amount of fresh air available for the complete combustion. In addition to it, the specific heat of the combustion products is more than that of the fresh charge. Hence, more amount of heat energy is required to raise its temperature, thereby reducing the in-cylinder temperature further.

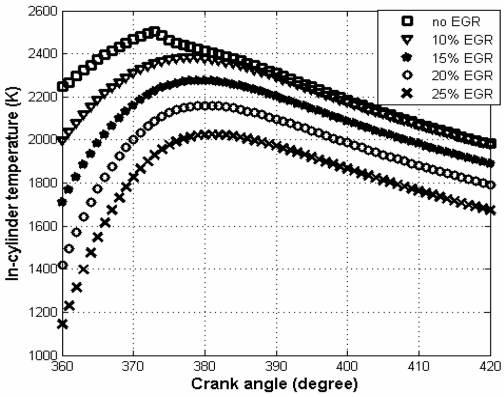

Figure 6. Variation of in-cylinder temperature with the crank angle for different fractions of the cooled exhaust gas recirculated.

The effect of in-cylinder temperature on the amount of cooled exhaust gas circulated also affects the in-cylinder temperature. The incomplete combustion due to the deficiency of fresh charge available for combustion also results in the reduced pressure. Altogether results in the reduction of power developed by the engine with the amount of cooled EGR. But the effect of dissociation and knocking could be reduced with it. Hence, resulting in a higher thermal efficiency. Figure 7. shows that, with the amount of cooled EGR, the thermal efficiency of the engine increases to an extent for a particular equivalence ratio and then starts to decrease further. This is because, for the equivalence ratios nearer to one, the in-cylinder temperature will be more and hence the dissociation will be more than that for the higher equivalence ratios. Hence, more amount of cooled EGR is necessary, resulting in the higher thermal efficiency. But at higher equivalence ratios, dissociation will be very less or almost absent, hence higher amount of EGR results in the reduction of power developed; which in turn affects the thermal efficiency.

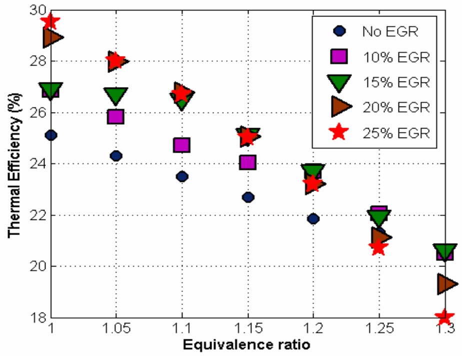

Figure 7. Variation of thermal efficiency with the equivalence ratio for different fractions of cooled exhaust gas circulated

5. CONCLUSION

Acoustic analysis is done on the sound signals recorded from the Yamaha FZ and Ambassador Diesel engine. The noise is filtered using the wavelet filters and power spectral density of the de-noised signal is plotted. From the results, it is clear that the fundamental frequency depends upon the firing frequency of the engine. Hence, the engine speed can be calculated from this. The engine speed found from the fundamental frequency almost confirms to the speed indicated by the digital tachometer. During the occurrence of knocking, the energy obtained for the fundamental frequency or any of its harmonics is speculated to change. In addition to it, any changes occurring in the high-frequency range also confirms the occurrence of knocking. As the fundamental frequency is changing with the engine speed, a database is to be made during the normal operating condition for all ranges of engine speed, to compare with real-time values.

Cooled exhaust gas can be used for reducing the in-cylinder temperature, thereby reducing the engine knocking, as well as the dissociation of gases at high temperature. This further increases the thermal efficiency of the engine with the amount of cooled EGR to an extent, beyond which the effect of the reduction in power due to EGR dominates over the effect of dissociation and knocking. From the results, it is seen that the thermal efficiency is increased up to 12% with the amount of EGR.

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NOMENCLATURE

T	Instantaneous temperature (k)
ρ	Density of gas mixture (kg/m^3)
m	Mass of gas mixture (kg)
$\dot{m}$	Rate of change of mass (kg/s)
Cp	Specific heat at constant pressure (kJ/ kg K)
R	Characteristic gas constant (kJ/ kg K)
h	Enthalpy of gaseous mixture (kJ/kg K)
Q	Instantaneous heat transfer (kJ/s)
γ	Specific heat ratio
A_T	Throat area (m^2)
n_v	Number of valves
C_D	Coefficient of discharge
h_g	Heat transfer coefficient of cylinder gas (W/ m^{2}K)
$\overline{S_p}$	Mean piston speed (m/s)
x_b	Mass fraction burned
α_{wall}	Fraction of mixture that burns in the slow combustion region
α	Adjustable constant that determines the duration of combustion
θ	Crank angle (degree)
θ_o	Crank angle at the start of combustion (degree)
$\Delta\theta$	Combustion duration (degree)
k_{wall}	Ratio of slow burn duration to standard burn duration
n	Adjustable parameter that fixes the shape of the combustion progress curve
r	Compression ratio
r_c	Crank radius (mm)
l	Connecting rod length (mm)
V_d	Displacement volume (m^3)
a	Scaling (or dilation) factor
b	Translation (or shifting) factor
$y_{high}[k]$	outputs of highpass filters
$Y_{low}[k]$	outputs of lowpass filters

Superscripts

*	Complex conjugate

Subscripts

u	Unburnt
b	Burnt
1	Upstream
2	Downstream
o	Standard state
in	Inlet
ex	Exit

АПРОКСИМАТИВНА АНАЛИЗА ЛУПАЊА МОТОРА СА УНУТРАШЊИМ САГОРЕ–ВАЊЕМ ПРИМЕНОМ WAVELET ТЕОРИЈЕ И КОНТРОЛА ЛУПАЊА РЕЦИРКУЛАЦИЈОМ ХЛАЂЕНИХ ИЗДУВНИХ ГАСОВА

Antoni Joseph, Jinsha Rajeevan, Shihabudeen H, Gireesh Kumaran Thampi

Лупање мотора представља препреку за побољшање перформанси мотора, па се степен компресије ограничава испод границе највишег степена корисности. Иако се лупање пројектовањем одржава знатно испод највишег степена корисности, оно се јавља у условима дуготрајног рада мотора услед опадања топлотног капацитета расхладног средства. Предмет наше студије је предвиђање појаве лупања, на основу звучних сигнала које ствара мотор, применом Wavelet теорије. Извршено је термодинамичко моделирање СУС мотора у циљу анализе побољшања његових перформанси, што би се могло постићи повећањем количине издувних гасова хлађених рециркулацијом. У току појаве лупања хлађени издувни гасови рециркулишу у циљу контролисања температуре у цилиндру мотора, па према томе и лупања мотора. Поред постигнуте редукције температуре, анализа показује да је топлотна искоришћеност мотора повећана за 12% рециркулацијом хлађених издувних гасова.