Detection and Identification of Detonation Sounds in an Internal Combustion Engine Using Wavelet and Regression Analysis

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***Abstract*— Improving efficiency and power in an internal combustion engine is always impeded by detonation (knock) problems. This detonation problem has not been explained fully yet. Quick and accurate detection of detonation is also in the development stage. This research used a new method of detonation sound detection which uses microphone sensors, analysis of discrete wavelet transform (DWT), and analysis of the regression function envelope to identify the occurrence of detonation. The engine sound was captured by the microphone; it was recorded on a computer; it was proceeded using a DWT decomposition filtering technique; it was then subjected to normalization and regression function envelope to get the shape of the wave pattern for the vibration. Vibrational wave patterns were then compared to a reference using the Euclidean distance calculation method, in order to identify and provide an assessment decision as to whether or not detonation had occurred. The new method was applied using Matlab and it has yielded results which are quite effective for the detection and identification of detonation and it is also capable of producing an assessment decision about the occurrance of detonation.**

Keywords—: microphone, knock, petrol engine, wavelets, filter

I. INTRODUCTION

A petrol engine is an internal combustion engine that works based on the the four-stroke cycle using regular, “premium” or *pertamax* (high octane) petrol, and an ignition system that uses spark plugs. This kind of motor is quite powerful and lightweight, but the fuel efficiency needs continue to strive to improve, namely by raising the compression ratio (CR) and fuel quality. However, ongoing efforts to improve the power and efficiency of the four-stroke internal combustion engine are always hampered by the occurrence of detonation (knock) problems.

Detonation is a phenomenon that is quite complicated to explain. However, to put it simply, misfiring that occurs by itself (auto ignition) during the compression stroke, will cause the engine to vibrate strongly, and will cause decreased power, overheating, and a waste of fuel; the engine will quickly become damaged. Therefore, the timing of ignition is always arranged so that it occurs as early as possible, but not until detonation occurs. Thus, detonation detection is very important to establish the exact time of ignition [1].

There are a variety sensors that can be used to detect detonation, of which the most accurate are pressure sensors inside the cylinder [2]. Piezoelectric accelerometer [3], ion current sensor [4] and optical sensors [5] can be used as knock sensors. This research used a microphone sensor, which is inexpensive and unaffected by engine heat, although there is a lot of noise that must be dealt with carefully when processing the signal.

Processing of the signals from the sensors needs to be carried out first, so that the detonation signal can appear more clearly. The engine’s vibration frequencies are recorded from 20 Hz to 20 kHz, while the frequency of detonation is approximately 5 Hz to 10 kHz [2]. It is therefore necessary to conduct the filtering first. Filtering can be done in several ways, including: conventionally, with a band-pass- filter [2]; the DFT (Discrete Fourier Transform) method [3]; time-frequency analysis based on the Wigner distribution [6]; the real signal mother wavelet method [4]; and the fuzzy-wavelet method [7] : the Laplace wavelet transform [8] ; the Kalman filter [9]. The filtering technique used for this research was wavelet decomposition (DWT) and wavelet packet reconstruction as required.

Identification to determine the occurrance of detonation can be carried out based on the intensity and recognition according to the vibration pattern. Widely used detection methods involve the intensity of detonation, which include: the LKI method of (Logaritmic Knock Intensity) [10]; the DKI method (Difference of Knock Intersity) [11]; the ARMA method (Auto Regressive Moving Averages) [12]; the multiple regression method [13]; the cross-correlation method [14]. The vibration pattern identification method using an accelerometer sensor on the engine [15] used wavelet. In this research, the identification of a wave pattern envelope that had been regressed was used along with an Euclidean calculation of distance as a reference.

The purpose of this research is to make proposals for new methods in the use of microphone sensors to record engine vibration signals, in the use of DWT for filtering, in making a function envelope to describe the vibration patterns combined with regression analysis for identification of detonation vibration patterns, and in a decision-making procedure that provides output that enables a conclusion to be reached by using the Euclidean distance calculation to set a benchmark as a reference.

A. Discrete Wavelet Transform Filter (DWT)

Discrete Wavelet Transform (DWT) was developed from the Continuous Wavelet Transform (CWT) and The DWT will be scaled and translated in the form of a discrete step [16]:

$$\psi_{j,n}(t) = \frac{1}{\sqrt{2^j}}\psi\left(\frac{t-2^j n}{2^j}\right) \quad (1)$$

The fields of the scale and time are discrete sample intervals and can be made orthogonal to dilation and translation with a selection of special parent wavelet.

With the approach of multi-resolution analysis (MRA), an algorithm can be quickly for the filter bank to compute the orthogonal wavelet coefficients. Orthonormal projection of f on the field and in which:

projection: $$P_{V_{j-1}}f = P_{V_j}f + P_{W_j}f \quad (2)$$

characteristics: $$a_j[n] = \langle f, \emptyset_{j,n}\rangle$$

relates to the field V_j

$$d_j[n] = \langle f, \psi_{j,n}\rangle$$

relates to the field W_j

$$\emptyset_{j+1,p} = \sum_{n=-\infty}^{+\infty} h[n-2p]\, \emptyset_{j,n} \quad (3)$$

$$\psi_{j+1,p} = \sum_{n=-\infty}^{+\infty} g[n-2p]\, \emptyset_{j,n} \quad (4)$$

Then the decomposition [16] :

$$a_{j+1}[p] = \sum_{n=-\infty}^{+\infty} h[n-2p]\, a_j[n] = a_j \star \bar{h}[2p] \quad (5)$$

$$d_{j+1}[p] = \sum_{n=-\infty}^{+\infty} g[n-2p]\, a_j[n] = a_j \star \bar{g}[2p] \quad (6)$$

Reconstruction [16] :

$$a_j[p] = \sum_{n=-\infty}^{+\infty} h[p-2n]\, a_{j+1}[n] + \sum_{n=-\infty}^{+\infty} g[p-2n]\, d_{j+1}[n] \quad (7)$$

Or

$$a_j[p] = \bar{a}_{j+1} \star h[2p] + \bar{d}_{j+1} \star g[2p]$$

Fig.1 shows the decomposition of discrete wavelet from rapid transformation giving 2 component filters into a low-pass filter (LPF) and high-pass filter (HPF). For input signals a_0 with LPF $\bar{h}[n] = h - n]$ and HPF: $\bar{g}[n] = h - n]$ will produce output [16] :

$$a_1[n] = a_0 \star \bar{h}[2n] \text{ and } d_1[n] = a_0 \star \bar{g}[2n] \quad (8)$$

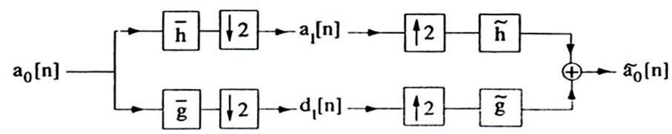


Fig. 1 : Mechanism of the input signal is filtered at decomposition and re-incorporated in the reconstruction [16]

This is essentially transformed into a filter system which consists of two filters, namely: the wavelet filter which is a high pass frequency filter or High Pass Filter (HPF) and the scale filter which is a low pass frequency filter or Low Pass Filter (LPF). Besides this, the scaling filter is the mean filter and the wavelet filter is the detailed filter, which can be seen in Fig. 2 .

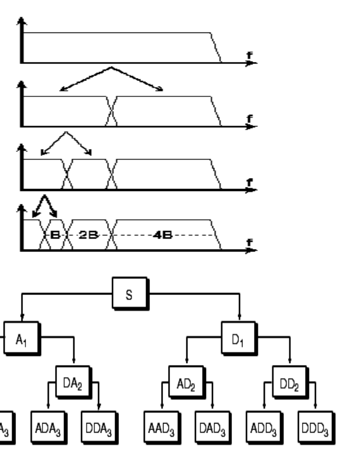
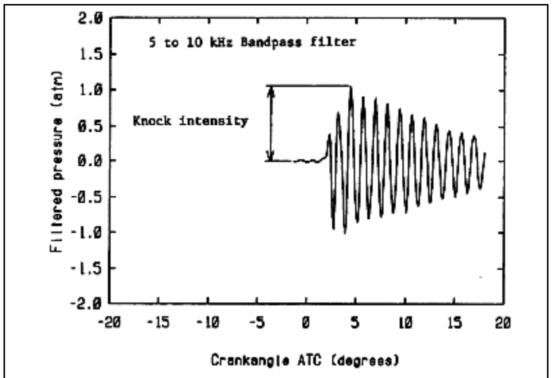


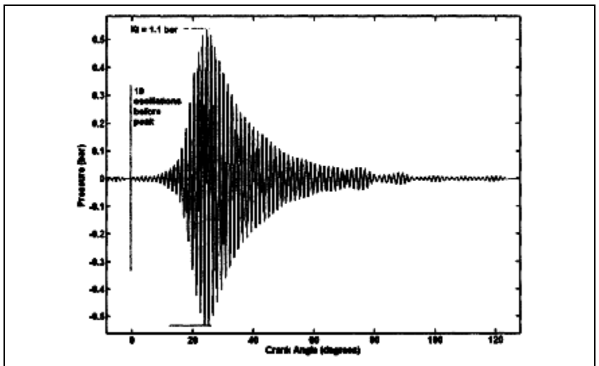
Fig. 2 : Structure of the discrete wavelet filter bank [17]

B. Detonation Wave Pattern

The detonation vibration wave pattern has already had a lot of researchers who have worked on it, including work on the characteristics of detonations that create the wave patterns as shown in Fig.3: [2], [18], that have similar patterns shapes.



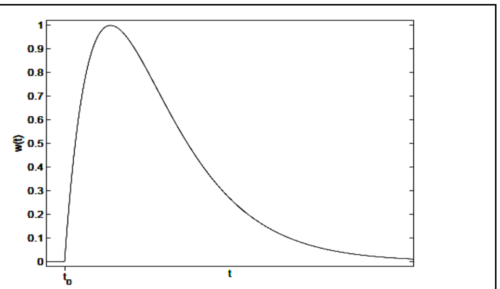
(Chun [2])



(Revier [18])

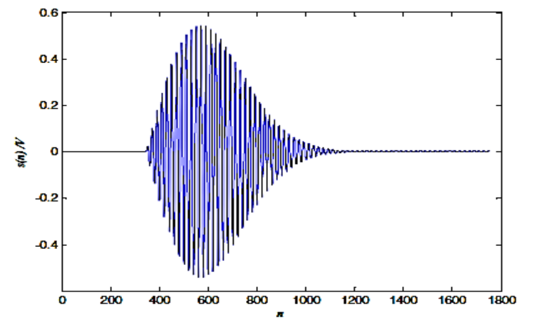
Fig. 3 : Detonation vibration wave pattern shape

A mathematical model for the detonation vibration wave pattern envelope shape was developed by, among others: [19] and [20] as shown in Fig. 4:



$$w_p(t) = \frac{t - t_{0,p}}{\tau_p} \exp\left(- \frac{t - t_{0,p}}{\tau_p} + 1 \right) \Theta(t - t_{0,p})$$

Zadnik et.all [19]



$$s(t) = \begin{cases} A(t - t_0)e^{-b(t-t_0)^2} \sin(2\pi f t + \varphi); t \geq t_0 \\ 0; t < t_0 \end{cases}$$

(Yang et.all [20])

Fig. 4 : Detonation vibration wave pattern envelope model

A comparison between normal engine vibration wave pattern and the detonation pattern is stated by, among others: [21], [22], as shown in Fig. 5:

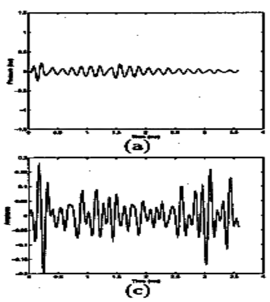
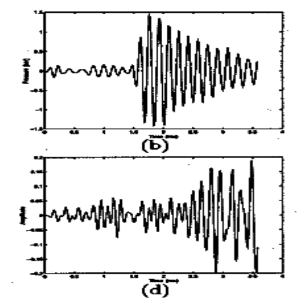
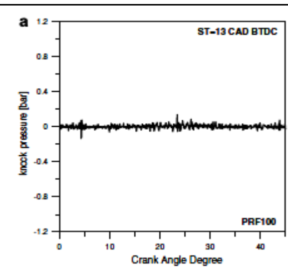
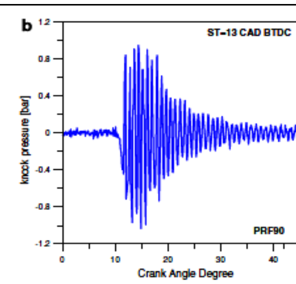
Normal (no-knock)	Detonation (Knocking)
 (Samimy et.all [21])	 (Samimy et.all [21])
 (Merola et.all [5])	 (Merola et.all [5])

Fig. 5 : Comparison of Normal (No Knock) and Detonation (Knock) vibration wave patterns

II. Research Method

The research was conducted by recording the sound of the engine while the vehicle was running and with particular settings in terms of gear, road speed, engine RPM, clutch and accelerator, that produced detonation (knocking). The vehicle used was a Toyota 1500 cc built in 1990.

The microphone is mounted in the engine space and the ignition timing signal is hooked up to the data acquisition tool and recorded on the computer at a rate of 44.1 kbps in order to carry out the sampling. The recordings of the signals obtained from the microphone were then filtered using the DWT technique, as shown in Fig. 6, which was carried out using Matlab software [17]: with the basic program using wavelet db31: `[a,d]=dwt(s,'db31')`

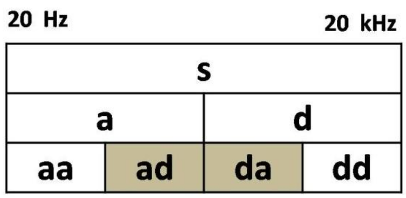


Fig. 6 : The DWT decomposition and filtering process along with the reconstruction of ad + da

Fig. 6: S is the source of the engine sound which is recorded with a microphone, and then decomposition of 2 levels (a,d →aa,ad;da,dd) with DWT and reconstruction (ad + da) are carried out, thus generating a signal corresponding to the band-pass -filter with a frequency of about 5 kHz to 15 kHz [13]. The results of this reconstruction are then normalized as shown in Fig. 7:

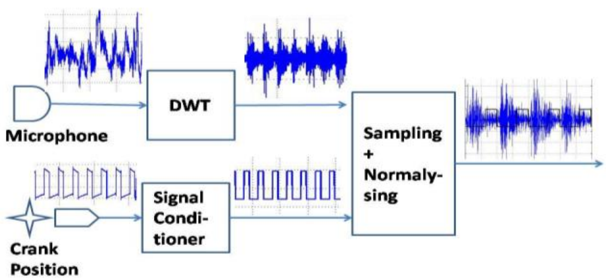


Fig. 7 : Signal processing with DWT

The signals are sampled and the results are then cut into pieces (windowing) in accordance with the ignition pattern of each cylinder, in order to identify the vibration patterns that occurred. For this identification, an envelope curve is created for the vibration pattern on the outer surface, as shown in Fig. 8:

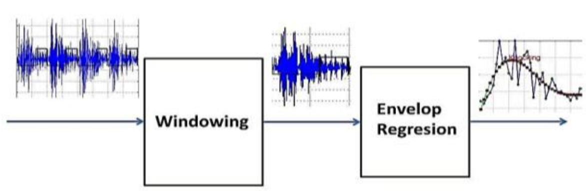


Fig. 8 : The process of windowing and making a regression pattern envelope

The envelope pattern is obtained and then an interpolation/regression is conducted to obtain a clearer pattern shape. The regression wave pattern shape will be identified by means of classification using an Euclidean calculation of distance as a reference. If the shape of the pattern is closer to the detonation pattern shape, then there has been a detonation (knocking). By the same reckoning, if the shape of the pattern is closer to a normal vibration pattern shape, then there has been no detonation (no knock) as shown in Fig. 9.

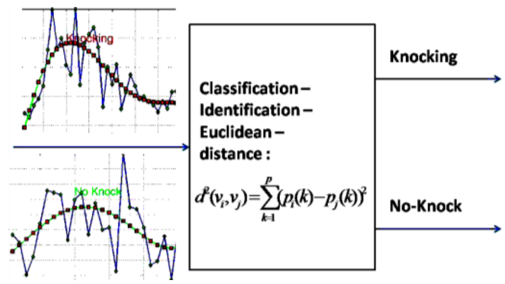


Fig. 9 : The process of identifying detonation vibration patterns

III. Results and Discussion

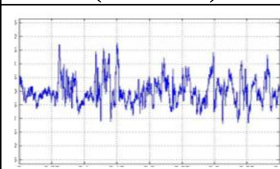
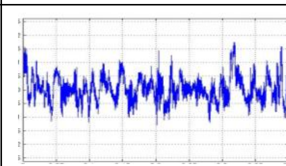
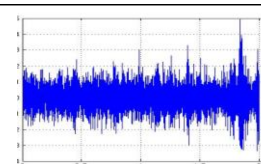
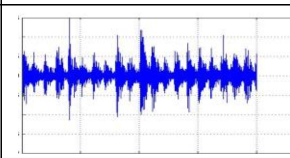
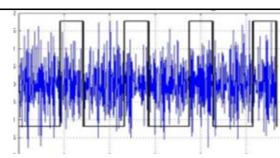
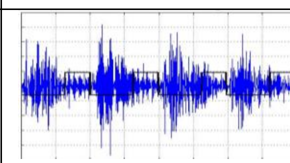
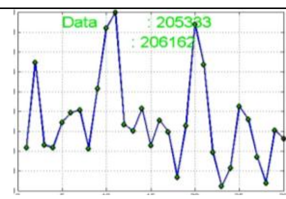
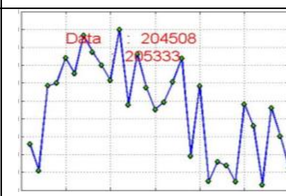
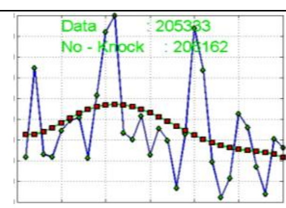
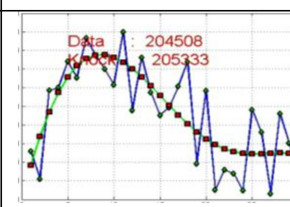
No.	The normal vibration pattern shape (no- knock)	The detonation vibration pattern shape (knocking)
1	 S	 S
2	 ad+da	 ad+da
3		
4		
5		

Fig. 10 : Results of DWT and normalized regression envelope function analysis

According to the results of recording the microphone signals, as shown in Fig.10-1, the normal signal input (no knock) and signal detonation (knocking) are very difficult to distinguish from one another, and detecting the detonation signal is particularly difficult. In Fig.10-2, the input signal is filtered by DWT, so the detonation vibration pattern is apparent. In Fig.10-3, the samples are cut (windowing) each 4 -cylinder cycle. In Fig.10-4, each cylinder cycle's signal is normalized function envelope with regression so that the wave pattern shape is clear and fairly easy to identify. In Fig.10-5, shows the process of identifying the detonation vibration pattern by using the Euclidean distance calculation which compares the normal vibration pattern (reference) to the detonation vibration pattern, and thus will assess whether or not there has been a detonation.

IV. CONCLUTIONS

Based on the research carried out, the following conclusions can be reached:

1. Inexpensive microphone sensors can be used to record the sound of the engine for the purpose of detecting detonation
2. DWT can be used for filtering detonation signals from other signals that originate from engine noise.
3. The regression technique from the normalized envelope function providesdetonation vibration wave form patterns.
4. The identification method using the Euclidean distance calculation assessed and established the occurrence of detonation.

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