Utilization of Detection and Identification of Detonation (Knock) Using a Wavelet to Create a Chart for a Petrol Engine's Characteristics

Agus Sujono [#1], R. Soekrisno [*2], Eka Firmansyah [*3], Oyas Wahyunggoro [#4]

[# 1]Faculty of Engineering, Sebelas Maret University (UNS),
PhD student of Electrical Engineering, Gadjah Mada University (UGM)
Surakarta , Indonesia
[# 4]Faculty of Engineering, UGM, Yogyakarta, Indonesia
[1] agus.sujono@ft.uns.ac.id
[4] oyas@ugm.ac.id
[*] Faculty of Engineering, UGM, Yogyakarta, Indonesia
[2] soekrisno67@gmail.com
[3] eka.firmansyah@ugm.ac.id

Abstract— The development of internal combustion engine always facing with the knock problem., Indeed, the characteristics of a motor engine itself is determined by the knocking issue. In this study, a method of knocking detection through simple microphone sensor has been developed. It incorporates discrete wavelet transformation (DWT) analysis and the regression function of the sound wave envelope to identify the occurrance of knock. After detecting the knock, a 3D engine ignition chart (characteristic) can be created as demonstrated in this paper.

Keyword—microphone, knock, internal combustion engine, wavelet, engine characteristic

I. INTRODUCTION

A knocking characteristic chart of an internal combustion engine is important to gain higher efficiency as the time immediately prior to the knock occurence is when the motor engine has its highest capacity. A petrol engine is an internal combustion engine that works based on the four-stroke cycle using regularpetrol fuel and an ignition system. This kind of motor is powerful and lightweight. Therefore, it is widely used for small engines with a capacity below 100 kW. The latest models the engine give a total fuel efficiency around 25%. Various parties continue to strive improvement for its power and efficiency normally through raising the compression ratio (CR) and fuel quality. Now, CR of about 10 and standard fuel quality based on octane rating (RON) has reached of about 98. However, ongoing efforts to improve the power and efficiency of the four-stroke internal combustion engine are always hampered by the occurrence of knock problems.

Knock 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. This knock will also occur when lower quality fuel is used and when ignition starts too early. However, when the timing of the ignition is too late, the engine power will decrease drastically. Therefore, the timing of ignition is always arranged so that it occurs as soon as possible, but not until knock occurs. Detection and identification of knock was carried out using a new method which uses a microphone sensor to record the engine's vibration signals, along with the use of DWT for filtering, and envelope-making functions to portray the vibration patterns combined with regression for identification of knock vibration patterns, recognition and decision-making procedures that provide output that is able to provide a conclusion by calculating the Euclidean distance benchmarked against a reference [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]. However, these sensors are expensive and not durable. Currently, the most widely used type is the vibration sensor (knock sensor) in the form of an electromechanical accelerometer, and there is also a piezoelectric accelerometer [3]. These sensors are also often troublesome because, being attached to the engine, they are affected by its heat and sometimes their screws can work themselves loose. Optical sensors with a quartz lens inside the combustion chamber are often restricted by the presence of crust on the chamber's surface [4]. An ion current sensor in the combustion chamber [5], [6], is often restricted by the electrode getting burnt. This study 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 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 Kalman filter method [7], the DFT (Discrete Fourier Transform) method [3]; time-frequency analysis based on the Wigner distribution [8]; the real signal mother wavelet method [5]; and the fuzzy-wavelet method [9]. The filtering technique used for this study 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], [13]); the multiple regression method [14]; the cross-correlation method [15]. The vibration pattern identification method using an accelerometer sensor on the engine [16] used wavelet. In this study, 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 study is to propose fo a new methods in creating an ingition timing chart of an engine by using microphone. Sound signal collected by microphone is then processed through DWT algorithm for filtering, in making a function envelope to portray the vibration patterns combined with regression analysis for identification of knock vibration patterns. Later, it becomes a basis for 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)***

Engine sound signals captured by microphone sensors need to be filtered in order that the detonation signal can be extracted. It can be done using the DWT technique, namely the approach of multiresolution analysis (MRA) can be conducted quickly to make an algorithm for the filtering (filter bank) to compute the orthogonal wavelet coefficients, followed by decomposition and reconstruction techniques that will be able to make the DWT technique as a low-pass filter (LPF) and a high-pass filter (HPF) [17].

Figure 1 shows the decomposition of a rapid discrete wavelet transformation provides two components of the filter into a low-pass filter (LPF) and a high-pass filter (HPF). For the input signal to the LPF and HPF a0: it will produce output [17]:

$$a_1[n] = a_0 * \bar{h}[2n] \quad \text{and} \quad d_1[n] = a_0 * \bar{g}[2n] \tag{1}$$

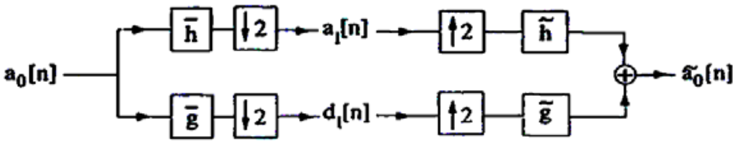


Figure 1: Mechanism of the input signal is filtered at decomposition and re-incorporated in the reconstruction [13]

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 Figure 2 .

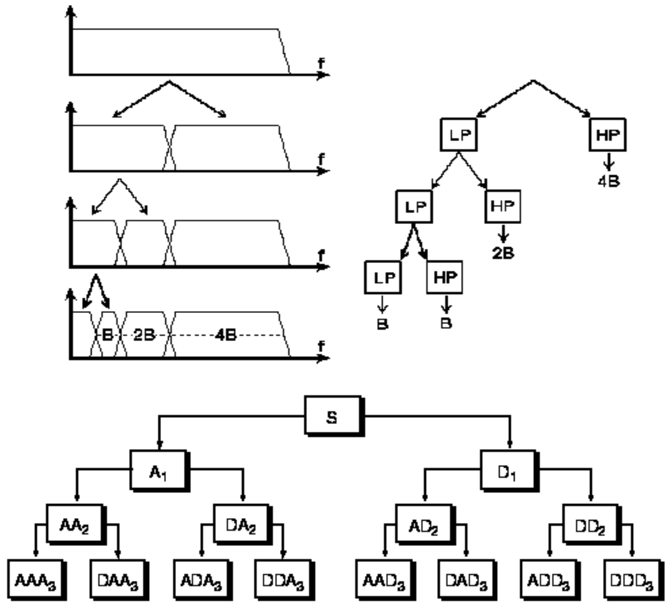
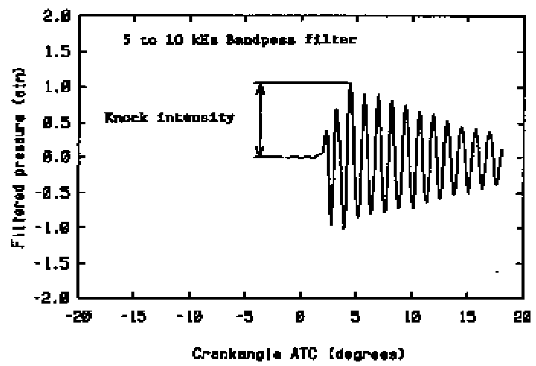


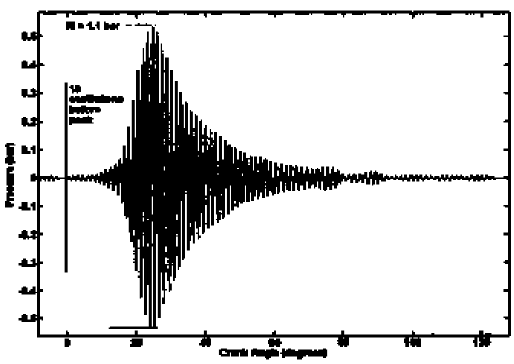
Figure 2: Structure of the discrete wavelet filter bank [18]

B. Detonation Wave Pattern

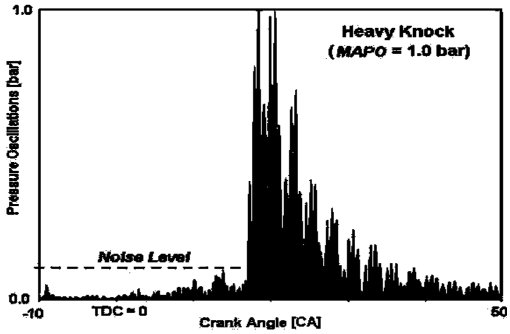
The detonation vibration wave pattern has already had a lot of researchers who have worked on it, including work on the characteristics of detonations that create the wave patterns as shown in Figure 3: Chun [2], Revier [19], Brecq et.all [20], (Behren et.all [21]) that have similar patterns shapes.



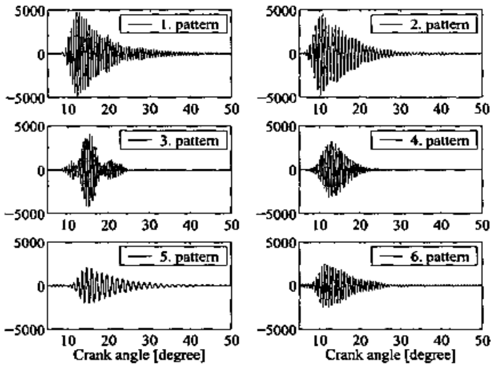
(Chun [2])



Revier [19]



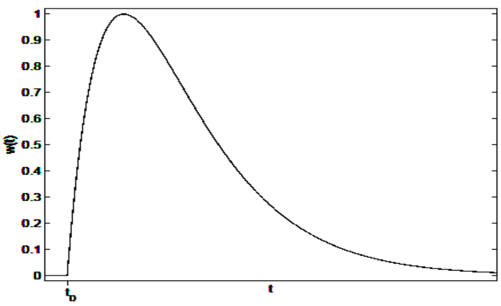
Brecq et.all [20]



(Behren et.all [21])

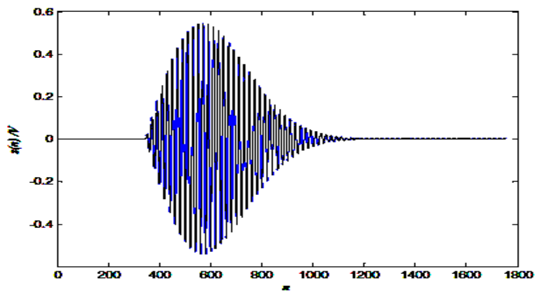
Figure 3: Detonation vibration wave pattern shape

A mathematical model for the detonation vibration wave pattern envelope shape was developed by, among others: Zadnik et.all [22] and Yang et.all [23] as shown in Figure 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 [22]



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

(Yang et.all [23])

Figure 4: Detonation vibration wave pattern envelope model

A comparison between normal engine vibration wave pattern and the detonation pattern is stated by, among others: Samimy et.all [24], Merola et.all [4] and Molinaro, et.all [25], as shown in Figure 5 .

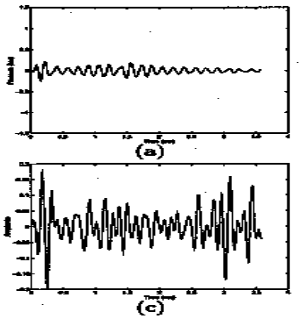
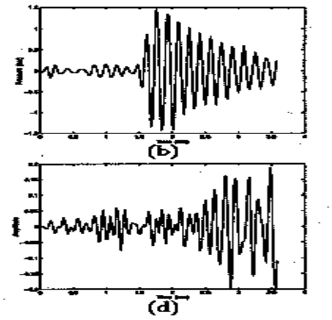
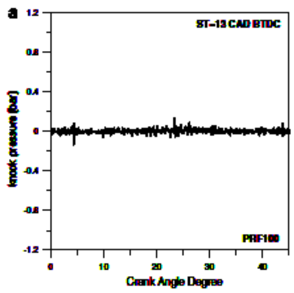
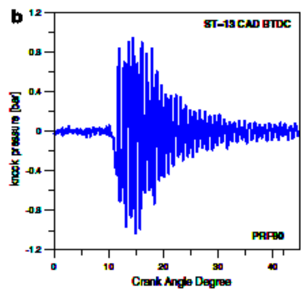
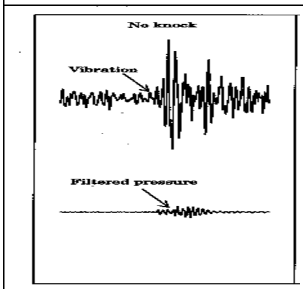
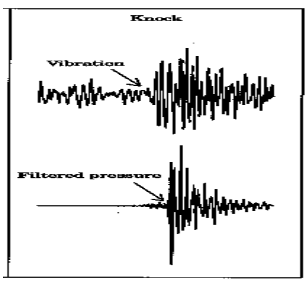
Normal (no-knock)	Detonation (Knocking)
 (Samimy et.all [24])	 (Samimy et.all [24])
 (Merola et.all [4])	 (Merola et.all [4])
 (Molinaro, et.all [25])	 (Molinaro, et.all [25])

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

C. Charactyeristic of an Internal Combustion Engine

An internal combustion engine, in order to provide maximum power and high efficiency, needs there to be a setting for the amount of fuel flow, the amount of air flow through the carburettor or injector throttle and ignition timing (spark advance). The most crucial thing is setting the ignition timing because the amount of spark advance depends on several factors, in particular: the number of revolutions and the size of the throttle valve opening, whereas improper ignition timing will reduce motor engine's performance. When the ignition is late, a lot of fuel is not burned so the power output is small fuel is wasted. When the ignition detonation occurs too quickly, the result is hard engine vibration, reduced power, wasted fuel, and the engine could be damaged. On the other hand, the engine will provide maximum performance when it is operated at around the time immediately prior to the detonation, which is referred to as the optimum ignition timing. The optimum ignition time is when detonation (knock) starts to be heard and is then pushed back 2 CAD (crank angle degrees). This moment is a time limit (margin) when it safe to give the MBT and is called the area of KL-MBT (knock-limited maximum brake torque) [26]. Therefore the chart of these characteristics provide the limits of the work area on ignition timing that gives maximum power and also can avoid the occurrence of a condition in which there is big detonation (knock) .

The optimum ignition time is a unique characteristic of a motor engine, which takes the form of a 3D data chart which is the location of the optimal ignition timing (spark advance) with the axis: high number of revolutions (engine speed), size of throttle opening (load) and ignition timing (spark advance), such as the example shown in Figure 6.

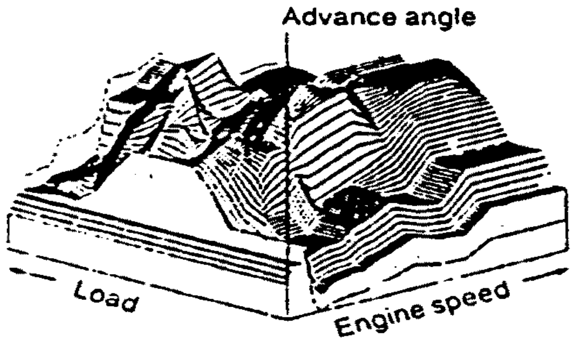
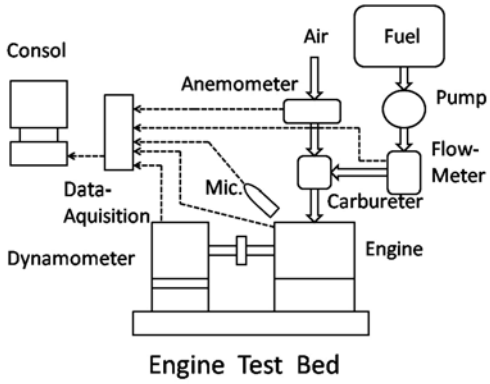


Figure 6: Characteristics of the 3D diagram of the spark advance (angle) [27]

II. RESEARCH METHOD

The study 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 1995 Suzuki 1600 cc. The engine was mounted on an Engine Test Bed (ETB), as shown in Figure 7.

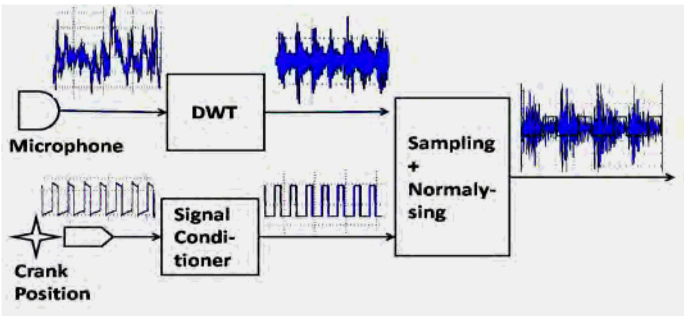
(a)



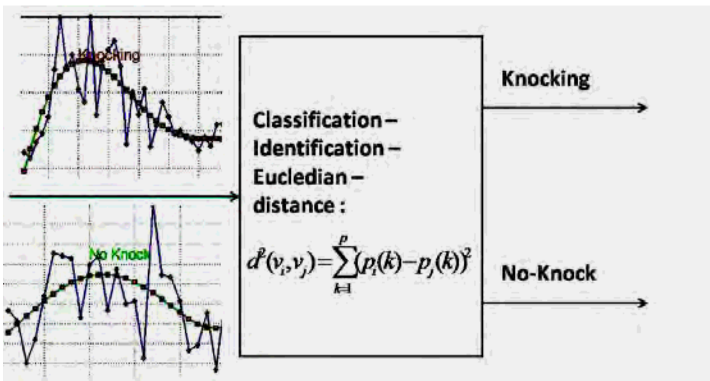
(b)

Figure 7 : Engine Test Bed (ETB) System : (a) picture, (b) schematic

The process of data collection and processing is as follows: the microphone is mounted close to the engine and the ignition timing signal is connected to the data acquisition tool and recorded onto a computer at a speed of 44.1 kbps for the purposes of sampling. The recorded signals that are obtained are then filtered using the DWT technique. A 2 level decomposition (a,d →aa,ad;da,dd) is conducted with the DWT and a reconstruction (ad + da) is conducted, thus producing a signal corresponding to the band-pass-filter with a frequency of about 5 kHz to 15 kHz [18]. The crank shaft position signal is also recorded onto the computer, as shown in Figure 8 (a). Then the detonation signal is combined with the crank shaft position signal so that sampling for each ignition cycle of the 4-cylinder is carried out.



(a)



(b)

Figure 8: Diagram of detonation signal processing (knock)

Data from this 4 cycle signal sampling are then cut into sections (windowing) in accordance with the pattern of ignition in each cylinder, so then the patterns of vibration that occurs can be identified. In this identification, an envelope wave is made which is the the outer shell of the vibration pattern. An interpolation/regression is later conducted on the envelope pattern obtained in order to get a clearer pattern form. The shape of this regression wave pattern will be identified by means of classification by calculating the Euclidean distance as the reference. If the shape of the pattern is closer to the shape of the detonation pattern, then there has been a detonation (knocking). On the other hand, if the shape of the pattern is closer to the shape of the normal vibration pattern, then there is no detonation (no-knock) as shown in Figure 8 (b).

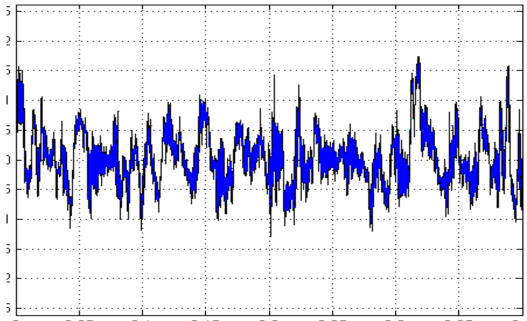
The 3D chart of the intensity of the characteristics of detonation (knock) is generated by running the engine at a steady rate of revs (throttle valve opened) which is adjusted, when the ignition timing (spark advance) is varied, which is advanced until detonation. At this time the following are noted: number of revs, power (torque), the size of valve openings and large spark advance (ignition timing).

III.RESULT AND DISCUSSION

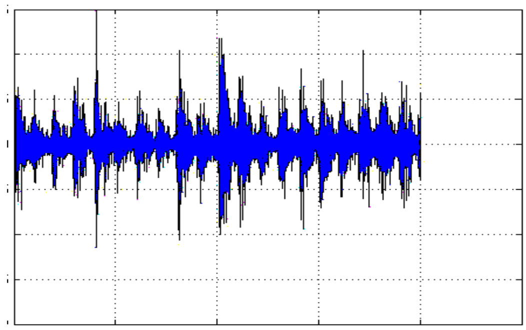
All paragraphs must be indented. All paragraphs must be justified, i.e. both left-justified and right-justified.

Identification knock waveform

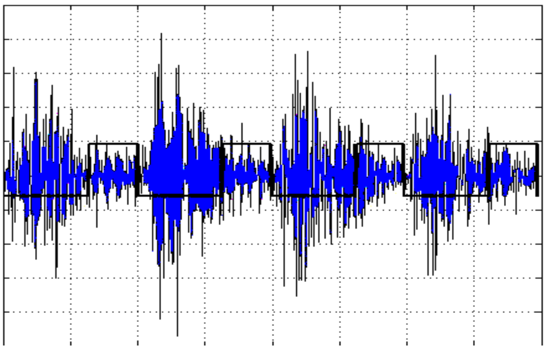
A. Identification knock waveform



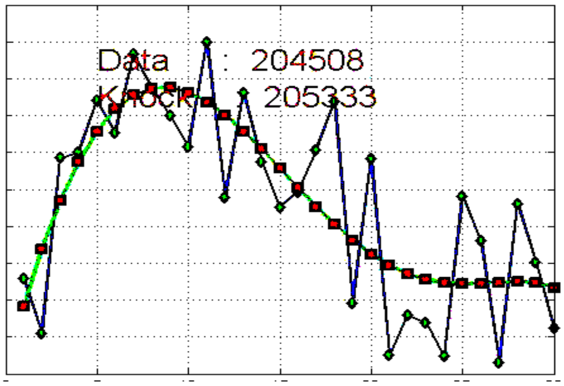
(a)



(b)



(c)



(d)

Figure 9: (a) microphone sensor signal recording, (b) Results of DWT analysis, (c) Sampling 4 ignition cycles, (d) regression of the function envelope that are normalized from one ignition cycle

From the results of the recording of the microphone signals, as shown in Figure 9 (a), the input signal from the detonation (knock) is captured and the eye can not identify any knock . But on Figure 9 (b) filtering results with DWT, therefore the detonation vibration pattern is visible. Figure 9 (c) sampling and windowing for one ignition cycle. Figure 9 (d) for 1 cycle 1 cylinder, the signal is normalized and function envelope regression is created to make a clear wave pattern shape and it is fairly easy to identify detonation (knock) with the calculation of the Euclidean distance as the reference signal.

B. Engine charachteristics

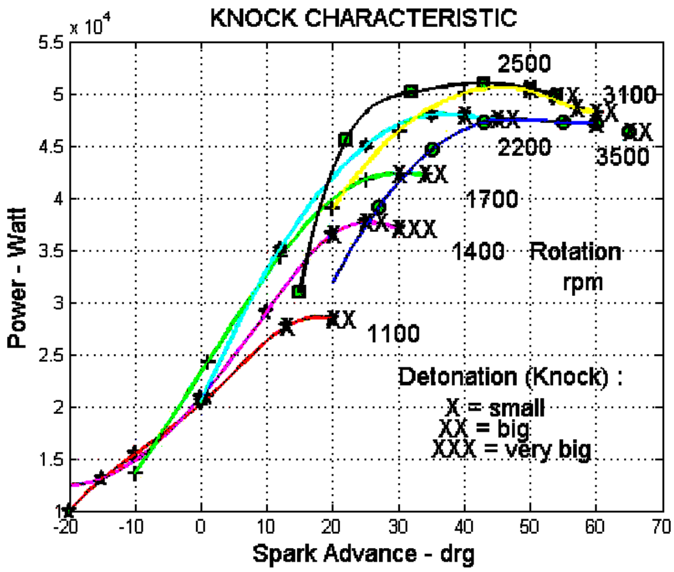


Figure 10: The results of the measurement of detonation at certain RPMs

Figure 10 is a characteristic level of engine knock which is the result of the measurement of detonation (knock) in particular with a large spark advance that is varied, which shows that for a particular rate of rotation, the greater spark advance results in greater power being generated. But if the spark advance is increased, detonation (knock) will occur, which initially will be small and increasing. For larger rotations, power will also increase, although there is also a maximum, i.e. at a rotation of about 2,500 rpm and about 30-40 degrees of spark advance, this results in maximum output power.

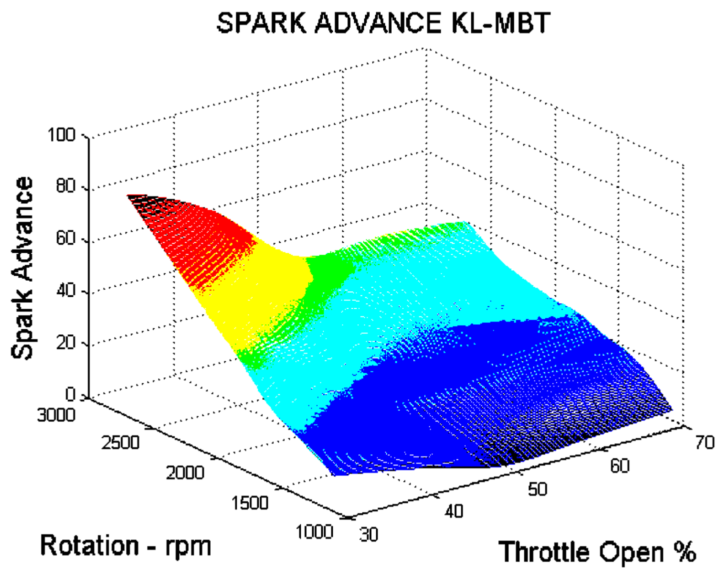


Figure 11: Chart of the engine characteristics to limit the optimum spark advance (KL-MBT)

Figure 11 is generated from the processing of the data from the knock characteristics for different degrees of throttle opening. This graph is the location of the position that is the limit of the KL-MBT spark advance, the optimum ignition timing before the detonation, which can generate maximum power. So it is a chart of maximum engine performance characteristics. A subsequent use is the using this chart as a reference (setting point) for the optimum ignition timing control in a variety of operating conditions.

IV. CONCLUSION

From the research that has been carried, it can be concluded that: for detecting the knock occurence, an inexpensive microphone can be used. With the help of a signal processing technique of DWT , regression of the function envelope and Euclidean distance calculations for identification of knock, these can be used later to create a 3D chart of an internal combustion engine's characteristics. The results of this chart can then be used as a benchmark (setting point) to control the ignition timing so that the engine can work optimally, but also avoid knock problems.

REFERENCES

[1] A. Sujono, R. Soekrisno, E. Firmansyah, O, Wahyunggoro, Detection and Identification of Detonation Sound in an Internal Combustion Engine Using Wavelet and Regression Analysis , Proceeding of International Conference on Electrical Engineering, Computer Science and Informatic (EECSI)-2014 , ISBN : 978-602-70504-0-2 , pages : 415-419, 2014.

[2] K.M. Chun, Characterization of Knock and Prediction of Its Onset in a Spark-Ignition Engine, dissertation Doctor of Philosophy in Mechanical Engineering at the Massachusetts Institute of Technology, USA, 1988.

[3] M.J. Kearney, Knock Signal Conditioning Using the DiscreteFourier Transform and Variable Detection Window Length, ISSN 0148-7191, Copyright © 2007 SAE International, Detroit, Michigan, USA, 2007.

[4] S.S. Merola, B.M. Vaglieco, Knock Investigation By Flame And Radical Species Detection In Spark Ignition Engine For Different Fuels, Istituto Motori – Cnr, Via G. Marconi, 8 80125 Napoli, Italy, Energy Conversion And Management 48 (2007) 2897–2910, 0196-8904/$ - see front matter _ 2007 Elsevier Ltd., 2007.

[5] Z. Zhang, N. Saiki, H. Toda, T. Imamura, T. Miyake, Detection of Knocking by Wavelet Transform using Ion Current,Fourth International Conference on Innovative Computing, Information and Control, IEEE, Instrumentation Systems Laboratory, Toyohashi University of Technology, Toyohashi, 441-8580, Japan, 2009.

[6] G. Ganti, Knock Modeling in Spark Ignition Engines and Study of The Effect of Combustion Instability of Knock, desertasi, PhD., Loughborough University of Tecnology, 1987.

[7] S. Ker, F. Bonnardot, I.L. Duva, Algorithm Comparison For Real Time Knock Detection, IFP,Technology, Computer Science and Applied Mathematics Division, 1 et 4, avenue de Bois Préau92 852 Rueil Malmaison Cedex – FRANCE, 2006.

[8] G. Matz, F. Hlawartsch, Time-Frequency Subspace Detectors and Application to Knock Detection, AE¨U Int. J. Electron. Commun. 53 (1999) No. 6, 1.6 c Gustav Fischer Verlag, Jena, Institute of Communications and Radio-Frequency Engineering,Vienna University of Technology,Vienna, Austria, 1999.

[9] J.M. Borg, K.C,. Cheok, G. Saikalis, S. Oho, Wavelet-based Knock Detection with Fuzzy Logic, CIMSA 2005 - IEEE International Conference onComputational Intelligence for Measurement Systems and Applications, Giardini Naxos, Italy, 2005.

[10] C. Hudson, X. Gao, R. Stone, Knock measurement for Fuel Evaluation in Spark Ignition Engines, Depatement of Engineering Science, Oxford University, UK, 2000.

[11] T.A.F. Soelaiman, New Strategies for Detecting Knock in Spark Ignition Engines, desertation, PhD., The University of Minesota., 1992.

[12] M.M. Ettefagh, M.H. Sadeghi, V. Pirouzpanah, T.H. Arjamandi, Knock detection in Spark Ignition Engine by Vibration Analysis of Cylinder Block, a Parametric Modeling Approach, Journal Mechanical System and Signal Procesing 22 (2008) 1495-1514, Tabriz, Iran, 2007.

[13] J.S. Souder, Closed-Loop Control Of A Multi-Cylinder Hcci Engine, dissertation Doctor of Philosophy in Mechanical Engineering, in theGraduate Division of the University of California, Berkeley, USA, 2004.
[14] H. Gerges, Mathematical Investigation For The Estimation Of Sound Noise From The Cylinder Pressure Noise For Direct Injection Diesel Engine, Master´S Thesis In Engineering Mathematics, Department Of Mathematics, Chalmers University Of Technology, Göteborg University, Göteborg, Sweden, 2006.
[15] F.K. Lu, A.A. Ortiz, J.M. Li, C.H. Kim, K.M. Chung, Detection Of Shock And Detonation Wave Propagation By Crosscorrelation, Aerodynamics Researchcenter, Mechanical And Aerospace Engineering Department, University Of Texas At Arlington, 214 Woolfhall, 500 West1 Ststreet, Arlington, Tx76019-0018,USA, Aerospace Science And Technology Research Center, National Chengkung University, Tainan, Taiwan, Republic Of China, Elsevier ltd. Allrightsreserved, 2008.
[16] J.H. Thomas, B. Dubuisson, E.M. Agn, D. Peltier, Engine Knock Detection From Vibration Signals Using Pattern Recognition, 1 Psa Peugeot Citro¨En, Direction Des Recherches Et Affaires Scientifiques, Centre Technique Citro¨En, 2 Route De Gisy; 78140 V´Elizy-Villacoublay, France, 2 Universit´E De Technologie De Compi`Egne, Umr Cnrs 6599 Heudiasyc, Bp 529; 60205 Compi`Egne Cedex, France, Meccanica 32: 431–439, 1997. © 1997 Kluwer Academic Publishers. Printed In The Netherlands, 1997.
[17] S. Mallat, A Wavelet Tour of Signal Processing, Academic Press, London, UK, 1998.
[18] M. Misiti, Y. Misiti, G. Oppenheim, J.M. Poggi, Wavelet Toolbox™ 4 Getting Started Guide, The Mathworks, Inc. 3 Apple Hill Drive Natick, Ma 01760-2098, 2010.
[19] B.M. Revier, Phenomena that Determine Knock Onset in Spark-Ignited Engines, thesis Master of Science in Mechanical Engineering at the Massachusetts Institute of Technology, USA, 2006.
[20] G. Brecq, J. Bellettre, M. Tazerout, A new indicator for knock detection in gas SI engines, International Journal of Thermal Sciences 42 (2003) 523–532, Elsevier SAS, 2002.
[21] S.C. Behrens, JF. Bohme, Fast Knock Detection Using Pattern Signals, Department of Electrical Engineering and Information Science, Ruhr-Universitat Bochum, 44780 Bochum, Germany, IEEE, 2001.
[22] M. Zadnik, F. Vincent, F. Galtier, E.A. Vingerhoeds, Performance Analysis Of Knock Detectors, Article Pr´Esent´E `A ‘‘18th International Conference On Systems Engineering’’,Coventry University, Coventry, AMPERE, 42 av. du G´en´eral de Croutte, 31100 Toulouse, France, 2006.
[23] W. Yang, K. Wang, C. Liu, Engine Knock Feature Extraction Based on Third-order Cumulants and Filter, International Conference on Measuring Technology and Mechatronics Automation, IEEE, 2010.
[24] B. Samimy, G. Rizzoni, A.M. Sayee, D.L. Jones, Design Of Training Data-Based Quadratic Detectors With Application To Mechanical Systems , The Ohio State University, Columbus, OH 43210, University of Illinois, Urbana, IL 61801, IEEE, 1996.
[25] F. Molinaro, F. Castanie, Signal Processing Pattern Classification Techniques To Improve Knock Detection In Spark Ignition Engines, Universite_ De La Reunion, Faculte_ Des Sciences, 15 Avenue Rene_ Cassin, 97715, Saint Denis Cedex,France And Enseeiht Gapse 2 Rue Camichel, 31071 Toulouse, Cedex,France, Mechanical Systems And Signal Processing (1995) 9(1), 51-62, 1995.
[26] R. Daniel, G. Tian, H. Xu , M.L. Wyszynski, X. Wua, Z. Huang, Effect of spark timing and load on a DISI engine fuelled with 2,5-dimethylfuran , Fuel 90 (2011) 449–458 , 0016-2361/$ - see front matter Crown Copyright _ 2010 Published by Elsevier Ltd. doi:10.1016/j.fuel.2010.10.008, 2011.
[27] Bosch , Automotive Electric , Electronic System , Germany, 1993.

AUTHOR PROFILE

Agus Sujono. PhD student of Electrical Engineering, Gadjah Mada University (UGM), Associate professor at Faculty of Engineering, Sebelas Maret University (UNS). His major research include internal combustion engine control, fuzzy logic control, automation industrian control and robotic.

R. Soekrisno, PhD. Associate professor at Mechanical Engineering, Gadjah Mada University (UGM). His major research include vibration enginering and material.

Eka Firmansyah, PhD. Associate professor at Electrical Engineering, Gadjah Mada University (UGM). His major research include power electronics and control.

Oyas Wahyunggoro, PhD. Associate professor at Electrical Engineering, Gadjah Mada University (UGM). His major research include electronics and inteligent control.