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Research Paper

Hilbert Transform Analyzer for Mechanical Fault Detection of Vehicle Alternators

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Abstract

Checking the alternator with mechanical measurements of moving parts takes sufficient time, especially in compact design engines. Therefore, this article presents a new method for alternator fault detection using the Hilbert transform application. The instantaneous amplitude and frequency are used as input variables for fault detection. Joint time-frequency analysis based on the wavelet analysis is also applied to identify the nonlinear characteristics. Various wavelet functions are examined, and some recommendations regarding the most suitable ones and the interpretation of the results are discussed. As a result, the backbone curve obtained from the instantaneous amplitude and frequency demonstrates the presence of the nonlinear phenomena, which can help make decisions about an alternator in normal conditions or indicate fault detection. From the test results, this method is very promising to be applied as part of vehicle's preventive maintenance.

Keywords: Preventive maintenance; Alternator; Hilbert analysis; Fault detection

Abstrak

Memeriksa alternator dengan pengukuran mekanis pada bagian yang bergerak membutuhkan waktu yang cukup, terutama pada mesin berdesain kompak. Oleh karena itu, artikel ini menyajikan metode baru untuk deteksi kesalahan alternator menggunakan aplikasi transformasi Hilbert. Amplitudo dan frekuensi sesaat digunakan sebagai variabel input untuk deteksi kesalahan. Analisis frekuensi waktu gabungan berdasarkan analisis wavelet juga diterapkan untuk mengidentifikasi karakteristik nonlinier. Berbagai fungsi wavelet diperiksa, dan beberapa rekomendasi mengenai yang paling cocok dan interpretasi hasil dibahas. Hasilnya, kurva tulang punggung yang diperoleh dari amplitudo dan frekuensi sesaat menunjukkan adanya fenomena nonlinier, yang dapat membantu membuat keputusan tentang alternator dalam kondisi normal atau menunjukkan deteksi kesalahan. Dari hasil pengujian, metode ini sangat menjanjikan untuk diterapkan sebagai bagian dari perawatan preventif kendaraan.

Kata-kata kunci: *Perawatan preventif; Alternator; Analisis Hilbert; Deteksi kerusakan*

1. Introduction

To maintain engine performance, scheduled maintenance must be performed especially on high-mileage vehicles. Engine oil, tires, brake shoes, filters, belts, and such components can be replaced on schedule. However, moving parts such as alternators, AC compressors, water pumps, superchargers, and engine-driven components generally haven't a replacement schedule; they are repaired or replaced only when a fault is detected. Therefore, predictive maintenance techniques, including vibration monitoring systems, are needed to make service decisions.

There are various causes regarding vibration, such as wear, resonance, unbalance rotation, and something like that. Processing and monitoring of vibration signals can be done in two ways; they are time-domain analysis and frequency-domain analysis. The time-domain analysis provides real-time signals and extracts signal characteristics such as amplitude values, time characteristics, and phase. The other is a frequency-domain analysis. Various information such as amplitude, phase, power spectrum, Fast Fourier transform (FFT), active window, and filtering is obtained by analyzing this signal. In the author's previous studies, predictive maintenance methods have been tested to the dynamic characterization of single-cylinder diesel engines [1], characterize the symptoms of disc brake [2], [3], and predict bearing damage by the excitation force that comes from the signal cell phone [4].

In the present study, we report a new method of predictive maintenance on the alternator. The standard gasoline engine must be able to operate with low-noise. However, fault on alternator bearing can produce rough sound and high vibration. We developed a wavelet packet-based method that allows the identification of system parameters directly from the generated data from the dynamic test structure using the Hilbert transform (HT) analysis [5]. HT was chosen because of a wider range of frequency resolutions, thus increasing the accuracy of identification [6]. The use of HT on the stator current amplitude is used for fault detection in the rotor [7].

Learning from the experiences of previous researchers, HT can be used in engine diagnostics, mechanical system identification, and signal component decomposition, which illustrates key concepts in actual mechanical signals [8]. HT is also able to make an analytical representation of the measured signal, which has a better energy concentration than the signal measured in the fractional domain [9]. For example, the HT method has been validly tested to detect faults in the rotor compressor [10], to process vibration signals from piston-liner wear in diesel engines [11], and to represent engine faults [12].

2. Literature Review

The Hilbert transform [13], [14] has become a promising signal processing tool for identifying nonlinear cases, connecting real and imaginary parts of the "Hilbert pair." The Hilbert pair is a complex function of the Fourier transforms, so the Fourier transform is closely related to the Hilbert transform at the same time signal. This allows signals in the time domain to be analyzed in the frequency domain. The method described in this section was developed by Feldman [8], [15] to obtain stiffness and damping characteristics in a single degree of freedom (SDOF) system.

Basically, two approaches can be used for analyzing, which are based on free vibration (FREEVIB) and forced vibration (FORCEVIB). In this work, we use FORCEVIB, which several numerical analyzes that take into account the corresponding representation of modal parameter relationships have been proposed by Tjahjowidodo [16] and Worden [17]. A large number of signals, including system vibrations with geometric non-linearity, can be converted into analytical signals in complex time and represented in the form of a combination of envelopes and instantaneous phases. The forced vibration equation of a single degree of freedom (SDOF) system is presented in Eq. (1).

$$\ddot{Y} + 2h_0(A)\dot{Y} + {\omega_0}^2(A)Y = \frac{X}{m} \tag{1}$$

where Y is the response signal, X is the forced excitation signal, m is the mass of the system, h_0 and ω_0 are the symmetrical viscous damping and stiffness characteristic of the system, respectively, which depend on the amplitude (A). According to the main properties of the non-overlapping spectra of HT, Eq. (1) can be converted by HT to the analytic signal form as presented in Eq. (2).

$$\ddot{Y} + 2h_0(A)\dot{Y} + {\omega_0}^2(A)Y = \frac{X(t)}{m} \tag{2}$$

Where $Y(t) = y(t) + j\tilde{y}(t) = A(t)\,exp[j\psi(t)$ is an analytic signal of the response of the system. Here, $\tilde{y}(t)$ is the HT of the real-value signal $y(t)$, while $X(t)$ is the analytic signal of the forced excitation. Substituting the analytic signal forms of $Y(t)$ and $X(t)$ together with the two derivatives of $Y(t)$, i.e.

$$\dot{Y} = Y(t)\left[\frac{\dot{A}(t)}{A(t)} + j\omega(t)\right] \text{ and} \tag{3}$$

$$\ddot{Y} = Y(t)\left[\frac{\ddot{Y}(t)}{A(t)} - \omega^2(t) + \frac{2j\dot{A}(t)\omega(t)}{A(t)} + j\omega(t)\right] \tag{4}$$

into Eq. (2), one can derive the representation of the corresponding modal parameters:

$$Y\left[\frac{\ddot{A}}{A}\omega^2+\omega_0{}^2+2h_0\frac{\dot{A}}{A}+j\left(2\frac{\dot{A}}{A}\omega+\dot{\omega}+2h_0\omega\right)\right]=\frac{X(t)}{m} \quad (5)$$

Solving two equations for the real and imaginary parts from Eq. (5), one can write the expressions for instantaneous modal parameters as

$$\omega_0{}^2(t)=\omega^2+\frac{\alpha(t)}{m}-\frac{\beta(t)\dot{A}}{A\omega m}-\frac{\ddot{A}}{A}-\frac{2\dot{A}^2}{A^2}-\frac{\dot{A}\dot{\omega}}{A\omega} \quad (6)$$

$$h_0(t)=\frac{\beta(t)}{2\omega m}-\frac{\dot{A}}{A}-\frac{\ddot{A}}{A}-\frac{\dot{\omega}}{2\omega} \quad (7)$$

where $\omega_0(t)$ is the instantaneous phase φ, while α (t)= Re [X (t) / Y (t)] and β (t) = Im = [X(t)/Y(t)] are the real and imaginary parts of input and output signals ratio according to expression

$$\frac{X(t)}{Y(t)}=\alpha(t)+j\beta(t)=\frac{x(t)y(t)+\tilde{x}(t)\tilde{y}(t)}{y^2(t)+\tilde{y}^2(t)}+j\frac{\tilde{x}(t)y(t)-x(t)\tilde{y}(t)}{y^2(t)+\tilde{y}^2(t)} \quad (8)$$

Where x(t), $\tilde{x}(t)$ is force excitation and its Hilbert transform, y(t), $\tilde{y}(t)$ y(t) is the vibration of the system and its is Hilbert transformer and these are the basic equations of the theory, the damper and spring characteristics fd (t) and fs (t) can be obtained trivially

$$f_d(A)=\omega(A)Ah(A) \quad (9)$$

$$f_s(A)=A\omega_0{}^2(A) \quad (10)$$

where $\omega_0^2(A)$ is the linear undamped natural frequency square as a function of the envelope, $h(A)$ is a damping coefficient as a function of the envelope, $A(t)$ is an envelope, $\omega(A)$ is an instantaneous frequency of the solution, $\alpha(t)$ and $\beta(t)$ are, respectively, the real and imaginary parts of the input/output ratio. Note that there are no assumptions on the forms of f_d and f_s, the method is truly non-parametric. The method based on Hilbert transform and extraction of the extraction of the instant frequency introduces errors when it is applied to damped system [15].

3. Method

To find out the dynamic characteristics of the alternator is done by measuring the frequency response function (FRF). Excitation force is applied to the alternator using a vibration analyzer. The excitation force is applied to the alternator surface in a vertical direction. The measured vibration response is carried out at six points, namely the center of the pulley parallel to the shaft (point A), the top of the alternator front body (point B), the side of the alternator front body (point C), the rear of the body parallel to the shaft (point D), the top of the alternator rear body (point E) and the side of the alternator rear body (point F) as presented in **Figure 1**.

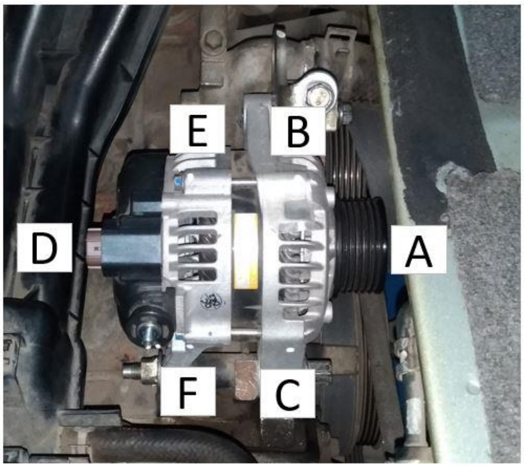

Figure 1. The measured vibration response point

The inner diameter of the alternator and in line with the placement of the sensor and the bump test point. FRF is carried out at point A on the radial axis. Point B is on the axial axis, while point C is on the axis, as shown in **Figure 2** (a), (b) and (c).

The research conducted on the characteristics of vibrations that occur in the three regions, especially on the alternator component, when the alternator is working at rest and gives a vibration input. In the measurement of FRF in this study, the frequency range is used is 1 - 1000 Hz.

Figure 2. Frequency response function measurement

The use of the frequency range is intended so that when testing the alternator is at rest, we can use where the frequency range can be used. While the photo set-up test to get the experiment data can be seen in **Figure 3**. The alternator is carried out a bump test in the C section, which is then read by a vibration analyzer. Data obtained from the measurement results are then analyzed using MATLAB.

The arrangement of the FRF measurement device is shown in **Figure 3** and it can be seen the types of equipment used, which are as follows:

- Accelerometer, which is used is a piezoelectric accelerometer made by Rion Japan Corporation type CCLD type, PV-571. Accelerometer serves to measure vibration response.
- Frequency span of 100 Hz with 1600-line analysis using the linear function window.
- Actual sensitivity Num 510 and actual sensitivity magnify x 0.012

Figure 3. Set-up experiment

4. Resuts and Discussion

We investigate the alternator by Hammer test. **Figure 4** demonstrates the change of accelerometer of the alternator. The response when the bump test was decreased from 17.5 to 2s. The transient signal phenomena is observed in the bump test response. **Figure 5** shows the results of the analysis using fast Fourier transform (FFT), in the frequency domain. FFT result obtained at point A natural frequency of 24 Hz, 153 Hz, and 253 Hz.

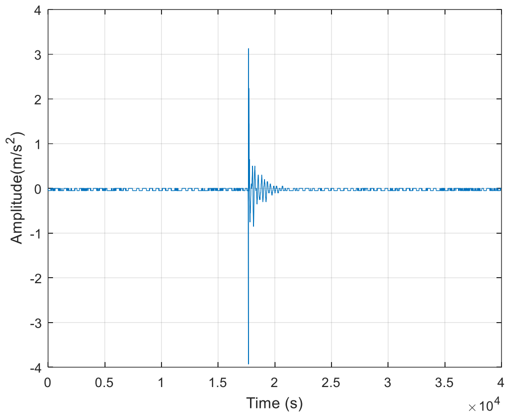

Figure 4. Bump test response in time domain

Furthermore, we did an analysis of **Figure 4** using the Hilbert envelope transform to know the phenomenon that occurs when these signals do Hilbert envelope analysis, the results of the Hilbert Envelope analysis can be seen in **Figure 6**.

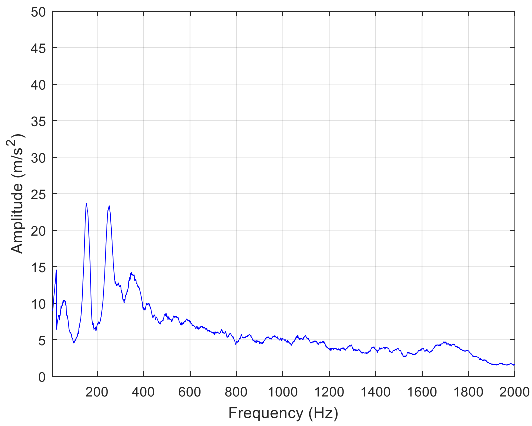

Figure 5. FFT analysis in the frequency domain

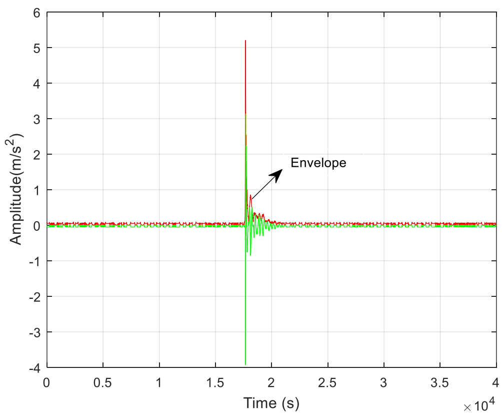

Figure 6. Results of hilbert transform envelope analysis

In order to optimize the results of the Hilbert transform analysis, we conducted a time capture method. The time capture is carried out aiming will only carry out analyzes in the range of about 1.5 to 2 s. the results of our time capture can be seen in **Figure 7**.

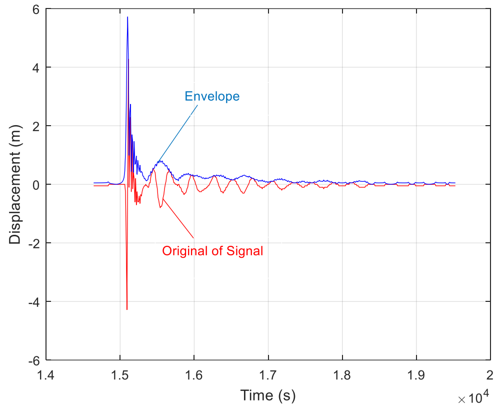

Figure 7. Time capture result

In the **Figure 8**, we can see the result of the envelope signal extraction from the vibration signal on the actuator when operating at 750 rpm using Hilbert transform (HT).

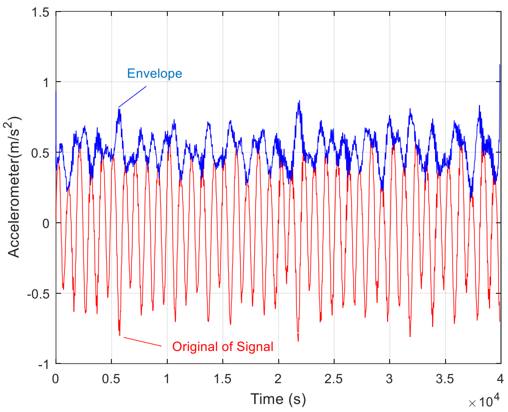

Figure 8. Envelope of the vibration signal on the alternator when operating at 750 rpm based on hibert transform

Figure 9 shows the instantaneous frequency estimation of the output response of the system, at the beginning and at the end of the envelope Hilbert Transform, noise terms appear in the instantaneous frequency because of the low amplitude. By pay attention to **Figure 9**, it is clearly seen that the Hilbert analysis has improved the instantaneous frequency estimation damage/good condition. In the reaction of 750 rpm rotation on the alternator for undamaged conditions, the frequency that occurs on the alternator does not experience a significant change compared to the frequency that occurs under damaged conditions. in the damaged alternator condition, instant frequency is very wide, approaching 0.02 Hz, compared to the undamaged condition, only below 0.005 Hz.

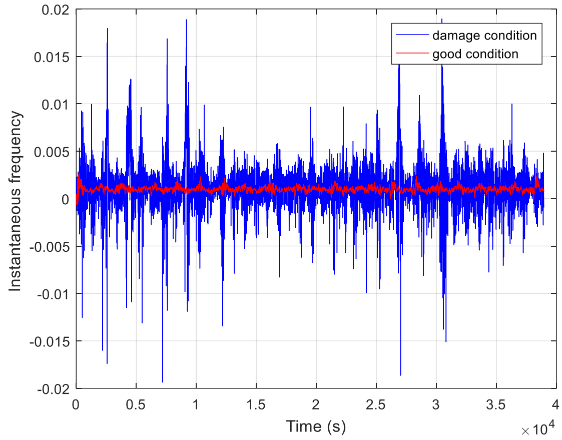

Figure 9. Instantaneous frequency extraction of damage and good condition vibration based on Hibert transform

The instantaneous amplitudes and their corresponding instantaneous frequencies are completely dependent on the domain of the amplitude envelope. The Alternator system the envelope will be a constant horizontal line and in turn the instantaneous amplitude and frequency are constant values as well. For this reason, an experiment of alternator systems undergoing force vibration is perfect for use with the Hilbert transform to find the backbone curve. A backbone curve natural frequency is one of the important characteristic of the nonlinear vibration. **Figure 10** shows the frequency response curve obtained from **Figure 9**.

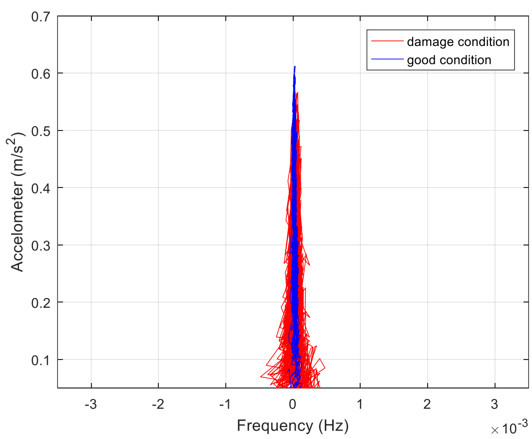

Figure 10. The backbone curve

Figure 10 is very important to evaluate the response of nonlinear system. The curve around 0 Hz seems to be a backbone curve that expresses the resonance conditions of nonlinear systems. in damaged condition the amplitude (Accelerometer) is lower than in good condition, and in good condition the backbone curves are more upright than the alternator condition is damaged. To increase the accuracy of the nonlinear capital parameters estimation, as shown in **Figure 11**, the stiffness increases with acceleration, this spring is said to be hard. This, due to the damaged condition, the spring constant that occurs changes compared to good conditions, which experiences a phase difference of about 30 degrees.

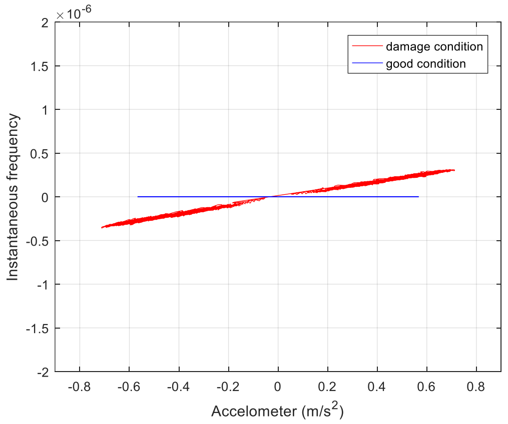

Figure 11. Restoring force extraction of damage and good condition

5. Conclusion

Hilbert analysis is applied to support the alternator and the instantaneous frequency of the Alternator in good condition and damaged, very helpful in identifying the condition of the alternator. This can be seen in the instantaneous frequency response, In the reaction of 750 rpm rotation on the alternator for undamaged conditions, the frequency that occurs on the alternator does not experience a significant change compared to the frequency that occurs under damaged conditions. The damaged/good condition of the frequency response was successfully identified by the Hilbert Transform method. The advantage of the Hilbert transform compared to the analysis is that the frequency response of the envelope signal shows the backbone curve of a linear phenomenon and changes in the spring stiffness parameters of the system change due to damage to the alternator.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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