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An Enhanced Energy Operator for Bearing Fault Detection

Ming Liang, Hamid Faghidi
University of Ottawa, Department of Mechanical Engineering
161 Louis Pasteur, Ottawa, Ontario, Canada K1N 6N5
liang@eng.uottawa.ca;hfaghidi@uottawa.ca

***Abstract* -** This paper reports an enhanced energy operator (EEO) method to detect bearing faults. This new energy operator exploits both the interference handling capability of a differentiation step and the noise suppression nature of the integration process. All these elements, i.e., differentiation, integration and energy operator, are implemented by a simple formula in one step. The main advantages of the proposed method include its simplicity, computational efficiency and the elimination of the bandpass filtering step and hence the resonance information. As such, it is suited to on-line bearing fault detection in a noisy environment with multiple vibration interferences. Our simulation studies have shown that the EEO method outperforms the conventional energy operator and the enveloping methods in handling both noise and interferences. Its performance has also been examined using our experimental data.

***Keywords*:** Energy operator, Differentiation, Integration, Bearing fault detection, Noise, Interferences.

1. Introduction

Bearings are among the most failure-prone mechanical components. An effective bearing condition monitoring method can prevent catastrophic failure of the equipment, and reduce cost of repair and down time. Many signal processing methods have been explored for bearing fault detection. However, weak fault signatures can be masked by noise from different external sources and internal mechanical components which makes bearing fault detection a very challenging task.

Vibration signals are commonly used for bearing condition monitoring because they are information-rich and the sensors are inexpensive and easy to implement. The vibration analysis methods for bearing fault detection can be classified into time-domain, frequency-domain, and time-frequency approaches. Statistical indicators such as root mean square, crest factor, and kurtosis are often adopted in the time-domain analysis (Liu et al., 2010).

To extract certain fault signatures, a signal in time domain can be transformed into frequency domain representation. The most applicable methods of the frequency-domain approach in industry are high-frequency resonance (HFR) techniques. When faults come in contact with the mating surface during bearing operations, they generate impulses and excite the resonance frequency (McFadden and Smith, 1984; Sheen, 2007). The HFR techniques extract the bearing fault signature, i.e., the fault characteristic frequency based on the excitation resonance information. The faulty features in the acquired signal manifest the impulsive vibration generated due to fatigue cracks or spalls on the surface of the bearing, namely inner race, outer race and rollers. The HFR technique involves bandpass filtering the raw vibration signal around high-frequency resonance band and amplitude demodulation (AD) prior to spectral analysis of the signal (McFadden, 1986). Its performance largely relies on designing appropriate bandpass filter which is ideally defined by an optimum bandwidth, and centre frequency according to the resonance frequency characteristics.

In real applications, it is desirable to develop online bearing monitoring methods that are less dependent on prior knowledge, nonparametric, non-filtering and computationally efficient. As such, a nonparametric method was suggested by Bozchalooi and Liang (Bozchalooi and Liang, 2009). This parameter-free fault detection algorithm employs the differentiation of a signal with maximum likelihood estimation as its basis. Furthermore, Liang and Bozchalooi presented another parameter-free method based on the energy operator approach for bearing fault detection (Liang and Soltani Bozchalooi, 2010).

They have demonstrated that the nonparametric methods such as the differentiation of signals and the energy operator have a great potential to replace the HFR techniques.

In this paper, we propose a new method to better handle high frequency noise and multiple interferences. This new method incorporates three elements: a) signal differentiation to improve signal-to-interference ratio (SIR), b) integration of the result of step a) to boost the signal-to-noise ratio (SNR), and c) fault detection from the improved signal. To facilitate applications, the three steps will be incorporated into a single enhanced energy operator (EEO). The paper hereafter is organized as follows: Section 2 describe the signal differentiation and integration, their effects on signal, and layer operator consisting of sequential operations of signal differentiation and integration. In Section 3, the enhanced energy operator (EEO) is introduced based on the energy operator and the layer operator concepts. The EEO method is then evaluated using both simulated and experimental data in Section 4. Comparisons with the enveloping and traditional energy operator are also presented in Section 4.The conclusions are given in Section 6.

2. Signal Differentiation, Integration and Layer Operator

This section explains the signal differentiation and integration, their implication in the context of bearing fault detection, and the layer operator developed based on signal differentiation and integration. The layer operator will be used to develop the EEO in the next section. Here we start with an illustrative example to explain that the low frequency signal components can be suppressed and the high frequency ones can be enhanced by differentiation.

For discrete signal, the differentiation of a signal $x(n)$ becomes difference, i.e.,

$$\mathrm{D}\big(x(n)\big) = x(n) - x(n-1) \tag{1}$$

Now we consider a signal with a low frequency component (0.1 Hz) and a high frequency component (10 Hz) of the same amplitude (Fig. 1(a)). The difference of the signal is shown in Fig. 1(b) which demonstrates that the low frequency component has been suppressed whereas the strength of high frequency one has been enhanced relative to that of the low frequency component. This effect is useful to suppress low frequency interferences and noise.

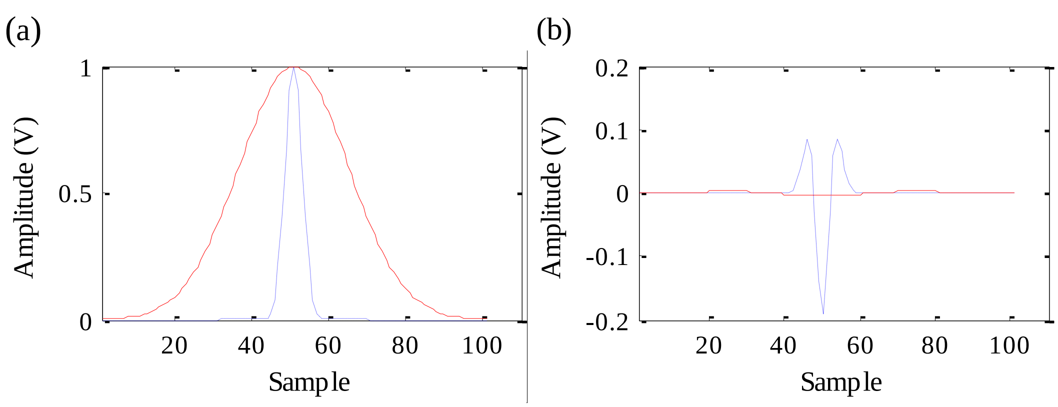

Fig. 1. (a) Signals with a long period (solid line) and a short period (dash line), and (b) their second differences (solid line: long period signal; dash line: short period signal).

In the case of discrete signal, numerical integration should be performed. For the sampled data, we set step $\Delta t = 1$. Then the trapezoidal rule for integration leads to

$$\mathrm{I}\big(x(n)\big) = x(n) + x(n-1) \tag{2}$$

Eq. (2) will be used in the following analyses. Signal integration can enhance signal in the presence of noise or increase signal-to-noise ratio due to its “smoothing” effects.

As illustrated above, differentiation can improve SIR while integration can enhance SNR. This leads to the development of a new operator called a layer operator (LO) consisting of sequential differentiation and integration operations to take advantages of both. The first order layer operator is defined as

$$\begin{aligned}\mathrm{LO}_1(x(n)) &= \mathrm{I}\left(\mathrm{D}\left(x(n)\right)\right) = \mathrm{I}\left(x(n)-x(n-1)\right)\\ &= \left(x(n)-x(n-1)\right)+\left(x(n-1)-x(n-2)\right) = x(n)-x(n-2)\end{aligned} \tag{3a}$$

The layer operator has a commutative property, i.e., changing the order of differentiation and integration does not affect the result. This is shown by

$$\begin{aligned}\mathrm{LO}_1(x(n)) &= \mathrm{D}\left(\mathrm{I}\left(x(n)\right)\right) = \mathrm{D}\left(x(n)+x(n-1)\right)\\ &= \left(x(n)+x(n-1)\right)-\left(x(n-1)+x(n-2)\right) = x(n)-x(n-2)\end{aligned} \tag{3b}$$

Similarly, a second order of LO can be defined as

$$\mathrm{LO}_2\left(x(n)\right) = \mathrm{LO}_1\left(\mathrm{LO}_1\left(x(n)\right)\right) = x(n)-2x(n-2)+x(n-4) \tag{4}$$

It should be emphasized that the differentiation and integration in the layer operator should both be done in one direction, i.e., either both are in backward or both are in forward direction, but not a mixed order.

3. The Enhanced Energy Operator

The energy operator is defined in continuous format as(Evangelopoulos and Maragos, 2006; Maragos et al., 1993)

$$\psi\left(x(t)\right) = \left(\frac{\mathrm{d}\,x(t)}{\mathrm{d}t}\right)^2 - x(x)\frac{\mathrm{d}^2\,x(t)}{\mathrm{d}t^2} \tag{5}$$

The conventional energy operator is sensitive to noise due to the differentiation operation. It is logic to expect that this shortcoming be mitigated by a new version of the energy operator that incorporating both differentiation and integration. As such, the new energy operator can be developed based on the layer operator. Analogous to the conventional energy operator but replacing the first and second order signal derivatives by the first order and second order LO’s, we obtain the EEO as follows:

$$\mathrm{EEO}\left(x(n)\right) = \mathrm{LO}_1^{\,2}\left(x(n)\right) - x(n)\mathrm{LO}_2\left(x(n)\right) = x^2(n) - x(n-2)x(n+2) \tag{6}$$

The fault detection can then be carried out using the EEO expressed above.

4. Evaluation of the EEO Method

The EEO method will be evaluated using both simulated and experimental data. In both cases, the EEO results are compared with those of the enveloping and traditional EO methods.

4. 1. Simulation

Here, we use the faulty bearing signal with multiple interferences that is generated using following equation(Liang and Bozchalooi, 2010):

$$x(t) = \sum_{m=-M}^{M} A_m e^{-\beta(t-mT_p-\tau_i)} \cos\omega_r \left(t - mT_p - \tau_i + \theta_m\right) u\left(t - mT_p - \tau_i\right) \tag{7}$$

where A_m is the mth fault impulse, T_p is the time period corresponding to the fault characteristic frequency, β the structural damping characteristic, ω_r the excited resonance frequency, τ_i represents the effect of random slippage of the rollers and $x(t)$ is the vibration signal containing $2M+1$ fault generated impulse.The parameters are set atA_m=1, β=1500, ω_r =2048 Hz,and T_p =0.008 and sampling frequency of 20,480 Hz. The fault frequency is $1/T_p$ =125 Hz. To test the EEO method, the signal is mixed with Gaussian noise (SNR= -15 dB) and four interferences with frequencies ω_{in} =5Hz, 27 Hz, 43 Hz, and 810 Hz respectively to reach an SIR of -20 dB. The signal mixture is shown in Fig. 2(a).

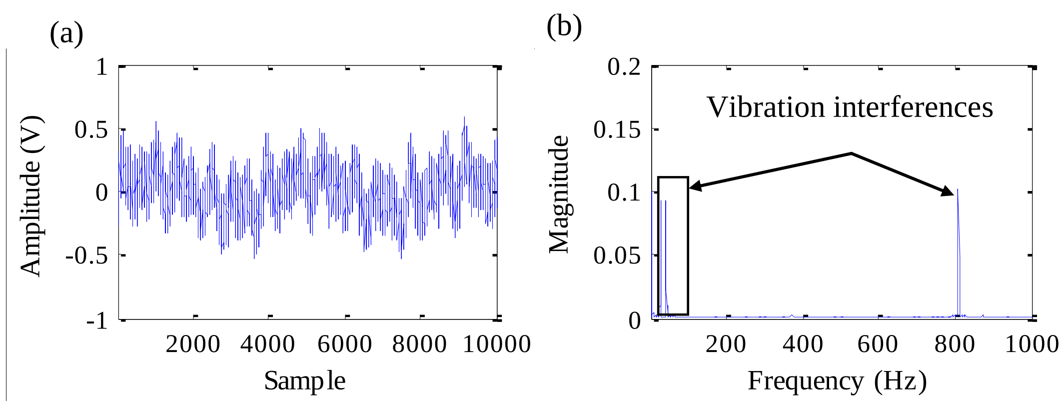

Fig.2.(a) Simulated faulty bearing signal with noise and multiple interfering components, and (b) the spectrum of the signal.

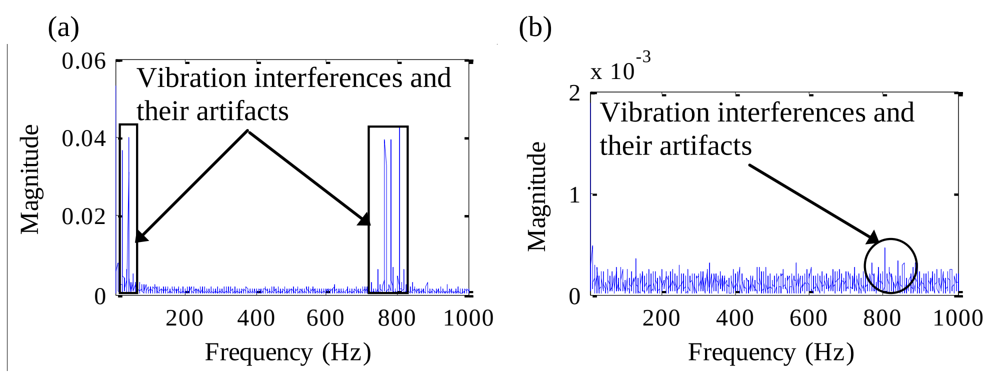

Fig. 3.(a) The envelope spectrum of the simulated signal (Fig. 2 (a)), and (b) spectrum of the energy operator result of the signal.

Fig. 2(b) shows the spectrum of the simulated signal. It can be seen that the interference components and noise dominate the entire spectrum. The results of the enveloping and energy operator methods are shown respectively in Figs. 3 (a) and (b). In Fig. 3(a), the spectrum is dominated by the interferences whereas in Fig. 3(b) the landscape is masked by heavy noise with some artifacts of the interferences. The fault frequency cannot be easily identified. These are expected because it is known that the amplitude demodulation becomes ineffective in the enveloping method in the presence of strong interferences and the energy operator method is susceptible to noise.

The proposed EEO method is then used to process the same data and yields the result of Fig. 4. The fault characteristic frequency and its harmonics can be easily recognized, indicating that the EEO can effectively suppress noise and enhance the detectability of the fault at the same time.

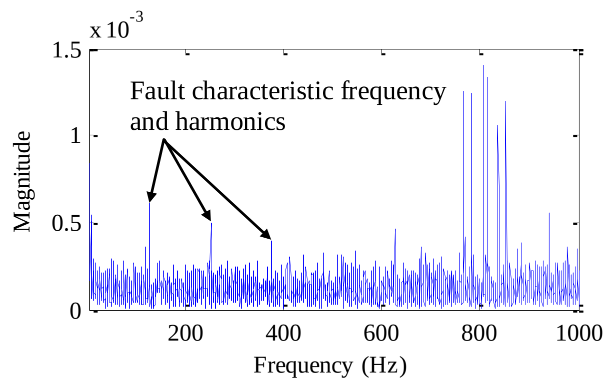

Fig. 4. Spectrum of the EEO result (the raw signal is shown in Fig. 2 (a)).

4. 2. Experiments

The experimental data are collected from a Spectra Quest Machinery fault simulator (MKF-PK5M) as shown in Fig. 5. Two bearings are mounted to support a steel shaft and two well-balanced mass rotors are installed on the shaft. An AC motor controlled by a PWM Hitachi inverter is employed to drive the simulator. The vibration signal is acquired using an accelerometer and an NI DAQ card.

The vibration data is saved in a PC with sampling frequency and other parameters specified by LabVIEW. Signal-processing is carried out using MATLAB on the PC.

Other details of the experiment are as follows:

- Shaft: 5/8" in diameter
- Mass rotors: 2" thick, 4" in diameter and 11.1 lbs each
- Bearings: Type ER10K with eight roller elements (balls). The inside, outside, pitch and ball diameters are respectively 0.625", 1.8500", 1.3190" and 0.3125".
- Accelerometer: PCB sensor, model 623C01 with sensitivity of 100 Mv/g and a sensitivity range of 1 Hz to 20 kHz.
- PWM Hitachi drive: SJ200-022NFU.
- DAQ card: NI PCI-6132 multi-function.
- PC: Pentium 4 of 2.52 GHz speed.

The shaft speed is set at 1503 RPM (25.1 Hz). The right bearing has a pre-seeded fault (created by manufacturer with unknown dimensions) on the inner race with the characteristic frequency of 124.19 Hz (=4.948 f_r, specified in the simulator user's manual). The gear meshing frequency is 174.1 Hz. To make the situation more complex, white noise (SNR=1dB) is added to the faulty bearing signal. The accelerometer is installed on the simulator base at a location away from the bearing but closer to the gearbox and belt pulley (Fig. 5). The vibration signal is sampled at 12,000 samples/s. The raw signal and its frequency spectrum of the bearing with an inner race fault are shown in Figs.6(a) and (b) respectively. The fault characteristic frequency of 124.19 Hz cannot be detected from Fig. 6.

The envelope spectrum of the raw signal and the spectrum of the energy operator are shown in Figs.7 (a) and (b) respectively. In the two cases, the fault signature cannot be easily observed. The EEO result is presented in Fig.8 where the fault characteristic frequency at 124.19 as well as two of its harmonics at 248.3 and 372.5 Hz can be clearly detected. This suggests that the EEO method is more effective than the enveloping and the conventional energy operator methods in detecting bearing faults in the presence of both noise and interferences.

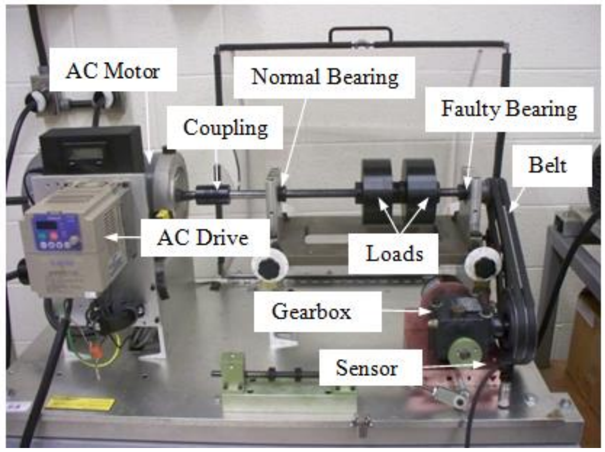

Fig. 5. Experimental setup.

(a) (b)

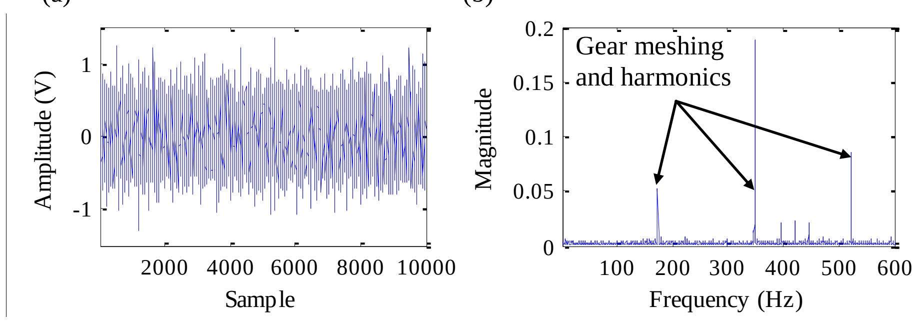

Fig. 6. (a) Measured signal of inner race fault, and (b) the spectrum of the faulty bearing signal.

(a) (b)

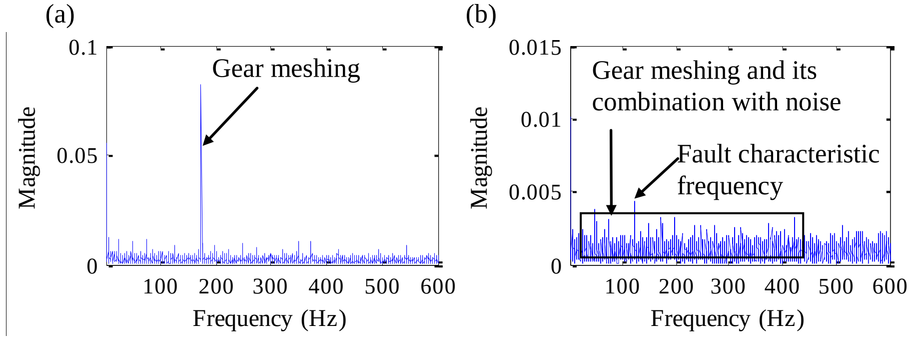

Fig.7 (a) Envelope spectrum of the same faulty bearing signal shown in Fig. 6(a), and (b) the spectrum of the energy operator result.

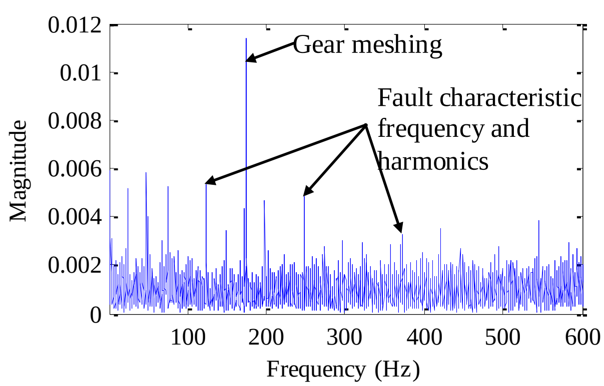

Fig. 8. Spectrum of the faulty bearing signal (shown in Fig.6(a)) obtained by the EEO method.

5. Conclusion

In this paper, differentiation and integration are jointly applied to develop an enhanced energy operator to improve both SIR and SNR.In the form of an energy operator, the proposed method is also fast since it requires only three points of data and easy to implement because of its structural simplicity. The performance of the EEO method has been compared favourably with the enveloping and the conventional energy operator methods using simulated data.The effectiveness of the EEO method is further validated experimentally.

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