Analysis of the sound signal to fault detection of bearings based on Variational Mode Decomposition

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Abstract. Damage detection in rotating machines is well established for vibration signals. Unfortunately, there are situations, where usage of vibration is not possible. Then, acoustic signal could be used instead. Unfortunately, usually acoustic signal are more noisy and require special treatment for obtain successful damage detection. In the paper we propose to use Variational mode decomposition (VMD) to omit noise for finding de-noise signal. We use vibration data to validate acoustic signal based procedure. The experiment was done on test rig with damaged bearings.

1. Introduction

Nowadays, bearings have a crucial role and pivotal position in various industries, such as petrochemical, mines, and other industries. Any failure in bearings may result in stopping production and losses to the factory. The operator can avoid the occurrence of such events by early detection of faults. Hence, the above reasons lead to the creation of condition monitoring (CM) systems to fault detection. In recent years, fault detection of bearings has been the subject of many articles and thesis. The most popular methods for fault detection of bearing include detection based on vibration signal [1, 2], and thermal analysis[3, 4]. Acoustic sound signal analysis is another method to detect bearings’ fault in recent years[5, 6].

The use of thermal cameras and image processing is another method that has been considered in fault detection in these years[7, 8, 9]. One of the most advantages of using thermal camera methods is that it can provide the proper location of the fault; also, this method does not need to contact the bearings. However, some disadvantages of these methods are high cost as well as time to heat bearings. Fault detection based on vibration signals has also been the subject of many researches[10, 11, 12]. The vibration-based methods can be used easily to detect fault in bearings. However, in this method, the vibration sensors (Acceleration, Velocity, or displacement) must be placed near or on the bearing cage. Also, the place of fault cannot be precisely determined. Utilizing acoustic sound signals is another method used for fault detection in some literature, such as[13, 14, 15]. Some advantages of this method are the acoustic signal it can be mentioned the installation is simple and the microphones can be placed anywhere near the target motor. Sensitivity to external noise can be considered as the most significant disadvantage of this method.
The main contribution of this research is to introduce an effective methodology based on acoustic signals. Our proposed approach in this study provides excellent results in identifying the bearings faults. Moreover, it represents the significant potential of sound signals as a non-destructive approach to bearings’ diagnosis fault. Also, the the VMD allows the decomposition of signals with better characteristics than some state of art methods such as EMD. Furthermore, the PSD method allows us to detect the signal-related spectrum associated with the fault.

The rest of the paper is organized as follows: Section 2 provides a theoretical foundation and background of this work. Section 3 describes the methodology introduced in this research. Section 4 investigates the experimental setup. Section 5 proposes the results of the experimental rig of the presented study. Lastly, the concluding remarks are highlighted in Section 6.[1]

2. Theoretical Background Scheme

In this section, the theoretical background of the proposed fault detection method will be discussed. In summary, three important mechanical and aerodynamic are dealt with sound production such as
- Fluctuating, displacement or injection volume (mass),
- Accelerating or fluctuating force on the fluid,
- Fluctuating shear stress in fluids.

The conventional devices consists of bearings, rotor, stator, motor frame, end bell, and fan, gears and etc. Mechanical and aerodynamic phenomena are the source of producing sound. In our case, the following sources can be listed as the most important issues
- Rotating of the rotor inside a stator (Pulsating volume)
- Rotating fan at the end of the motor (Pulsating force)
- Rotating flywheels (Pulsating force)
- Displacement of the screw (Pulsating volume).
- UAV sound
- Environment’s noise

Therefore, it is evident that if any fault is happened in device’s components during its working condition, the system sound will also change.

2.1. Variational Mode Decomposition

VMD is one of the recently developed powerful approaches for adaptive signal processing that can decompose a multicomponent signal into band-limited IMF. The VMD method can be defined as a bound up variational problem:

\[
\min_{\{u_k\}, \{\omega_k\}} \left\{ \sum_{k=1}^{K} \left\| \partial_t \left[ (\delta(t) + \frac{j}{\pi t}) \times u_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \right\} \text{subject to } \sum_{k=1}^{K} u_k(t) = f_1
\]

where \( \{u_k\} = \{u_1, u_2, ..., u_K\}, \{\omega_k\} = \{\omega_k, \omega_k, \omega_k\}, \) and \( K \) indicate the number of the bounded-limited IMFs.

By using quadratic penalty and Lagrangian multipliers and introducing a can solve the mentioned equation. A description of augmented Lagrangian is:

\[
L(\{u_k\}, \{\omega_k\}, \lambda) = \alpha \sum_{k=1}^{K} \left\| \partial_t \left[ (\delta(t) + \frac{j}{\pi t}) \times u_k(t) \right] e^{-j\omega_k t} \right\|_2^2 + \left\| f(t) - \sum_{k=1}^{K} u_k(t) \right\|_2^2
\]
\( \langle \lambda(t), f(t) - \sum_{k=1}^{K} u_k(t) \rangle \) (2)

Equation (2) is then solved with the alternate direction method of multipliers (ADMM). All the bounded limited IMF components gained from solutions in spectral domain are described as follow:

\[ \hat{u}_k(\omega) = \frac{\hat{f}(\omega) - \sum_{i \neq k} \hat{u}_i(\omega) + (\hat{\lambda}(\omega)/2)}{1 + 2\alpha(\omega - \omega_k)^2} \] (3)

Where the \( \omega_k \) is computed at the center of gravity of the corresponding component’s power spectrum. And the update strategy of \( \omega_k \) is based on the following equation:

\[ \omega_k = \frac{\int_{0}^{\infty} \omega |\hat{u}_k(\omega)|^2 d\omega}{\int_{0}^{\infty} |\hat{u}_k(\omega)|^2 d\omega} \] (4)

After that the inverse Fourier transform of \( u_k(\omega) \), then the corresponding bound limited IMF component can be included. to find more detail of the VMD algorithm could be found in the literature.

2.2. Spectrogram
Spectrogram is a sequence of Fourier transforms of a windowed signal. Spectrogram provides the time-localized frequency information for situations in which frequency components of a signal vary over time, whereas the standard Fourier transform provides the frequency information averaged over the entire signal time interval. For more information are provide in following references.

3. Methodology
The suggested methodology is demonstrated in Figure 1. In the first step, the system is tested in two cases: bearing fault and bearing fault with UAV noise. Next, acoustic sounds with microphones will be recorded. The acoustic sound signal is captured as an 8-bit resolution with a sampling frequency of 50 kHz. Consequently, the acoustic sound signal is stored in the memory, then, we utilize the VMD method to decompose signals. Furthermore, we transform the decomposed signal to the time-frequency domain with spectrogram in MATLAB 2020b in the next block. All in all, once the decomposition mode spectra are obtained, the condition of the motor is identified by analyzing signature frequencies with the aid of faults on the signal.

4. Experimental Setup
In this work, the Brüel and Kjær microphone type 2671 taken into account to record sound signals in two state one is located in near bearing and another is located on UAV. This microphone record sound for 5 seconds, they start to record simultaneously. More detailed information regarding microphone is given in Table 1. It should be noted that microphone within the virtual circle border of approximately 1.50-meter diameter, and the center is a device.
Figure 1: Simulation procedure flowchart

(a) Test rig examined in the experiment.
(b) Brüel & Kjær 4189-A-021 microphone with type preamplifier.
(c) DJI Mavic Mini quadrotor drone.

Figure 2: Hardware used in the experiment.
Table 1: Detailed information regarding the Microphone

| Microphone    | Kind Of Microphone | Sampling rate | Resolution |
|---------------|-------------------|---------------|------------|
| Bruel and Kjaer2671 | cardioid          | 50 kHz        | 8bit       |

5. Results and Discussion
In this section, the obtained results dealt with experimental tests for further verification are discussed.

5.1. Bearing Fault
This section of the analysis is focused on gathering data without UAV’s contribution to background noise. Also, in this section microphone located near a faulty bearing to gathered data when the device is worked in steady-state mode. In Fig. 2 a.a, the raw signals of faulty bearing that gathered by the data acquisition system are illustrated. In Fig. 3 a. b Spectrograms were generated for the sound signal. Time-frequency transformation of the sound signals is shown periodically impulses in the signal. Amplitude modulation of the sound signals was investigated by calculating the envelope of the signal and transforming it to the frequency domain. The resulting envelope spectra are shown in Fig 3 a.c. The frequency of the periodic repetition of the impulses can not be estimated based on the envelope spectrum of the sound signal. To make an informative result VMD was applied to the raw signals based on the observation that cyclic changes of magnitude are present primarily in the high-frequency band on the spectrograms. In Fig 3 b Time series of all IMFs of raw signal is demonstrated it as can be seen in the figure... in the last IMFs, the noise is well eliminated and shows the signal of harmonic behavior. In Fig 3 c Spectrogram and envelope spectra calculated for the decompose signal (IMF8) and the original signal and as can be seen envelope spectra calculated for the decompose signal (IMF8) distinctly expose modulation of the signals with impulsive periodic components.
5.2. Bearing Fault with UAV noise
The next part of the research concerned analogous measurement performed in the presence of the noise generated by a hovering UAV. The impact of the noise characteristics is qualitatively greater in the case of the sound recorded by the microphone decreasing signal-to-noise ratio. In Fig. 4 a.a, the raw signals of faulty bearing that gathered by the data acquisition system are illustrated. In Fig. 4 a. b Spectrograms were generated for the sound signal. Time-frequency transformation of the sound signals is shown periodically impulses in the signal. As we expected the impulsive local damage component is harder to examine based on time-frequency decomposition of the acoustic signal in these background conditions. Amplitude modulation of the sound signals was investigated by calculating the envelope of the signal and transforming it to the frequency domain. The resulting envelope spectra are shown in Fig 4 a.c The frequency of the periodic repetition of the impulses can not be estimated based on the envelope spectrum of the sound signal. To make an informative result VMD was applied to the raw signals based on the observation that cyclic changes of magnitude are present primarily in the high-frequency band on the spectrograms. In Fig 4b Time series of all IMFs of raw signal is demonstrated it as can be seen in the Fig 4 c in the last IMFs, the noise is well eliminated and shows the signal of harmonic behavior. In Fig 4 c Spectrogram and envelope spectra calculated for the decompose signal (IMF8) and the original signal and as can be seen envelope spectra calculated for the
decompose signal (IMF8) distinctly expose modulation of the signals with impulsive periodic components.

![Image](b) IMF TimeSeriesand orgina.

![Image](c) Main signal a) Time series . b) Spectrogram c) envelope and de-noised signal d) Time series . e) Spectrogram f) envelope.

Figure 4: Acoustic signal effected with UAV noise

6. Conclusion

This work presented a reliable and accessible methodology used for fault detection of a bearing in a steady-state mode. The result demonstrated the excellent performance of this methodology. The VMD was used to decompose the acoustic sound signals. It is feasible to pick out those special decompose that contains the essential information for detecting the faults and eliminating, at the same time, unfavorable signal components. These decomposition methods were used as a preprocessing stage and modify the estimation of the spectrum acquired by spectrogram and envelope spectrum, which can increase the ability to observe and identification of spectral components of the fault signal. Besides, sound signals fall under the category of non-destructive methods, which do not create any disadvantages on the engine performance during its operation, which can be used to detect many systems’ faults, especially in a harsh environment.
7. Acknowledgments
Supported by the Foundation for Polish Science (FNP). This activity has received funding from European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation. This work is supported by EIT RawMaterials GmbH under Framework Partnership Agreement No. 19018 (Autonomous Monitoring and Control System for Mining Plants - AMICOS).

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