A NEW METHOD OF VIBRATION ANALYSIS FOR THE DIGANOSIS OF IMPELLER IN A CENTRIFUGAL PUMP

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Centrifugal pumps are widely used in many important industries such as power generation plants, chemical processes and petroleum refiners. The condition monitoring of centrifugal pumps is highly regarded by many researchers and users to minimize unexpected breakdowns. Impellers are the core parts of pumps but often appear early damages due to flow cavitation and erosion. This paper investigates a new approach to monitoring the conditions of impellers using surface vibration with advanced signal analysis. As overall vibration responses contain high level of broadband noises due to cavities and turbulences, noise reduction is critical to develop reliable and effective features. However, considering the modulation effect between rotating shaft and blade passing components, a modulation signal bispectrum (MSB) method is employed to extract these deterministic characteristics of modulations, which is different from previous researches in that broadband random sources are often used. Experimental results show that the diagnostic features developed by MSB allow impellers with inlet vane damages and exit vane faults to be identified under different operating conditions.

1. Introduction

Condition monitoring (CM) of pumps is an important mission for maintaining production safety and efficiency in many industries such as chemical and petroleum processes. To improve the monitoring performance, many studies have been conducted in recent years with more advanced data analysis methods, which are applied to the surface vibration of the pump house.

Zhou et al [1] introduced a method for centrifugal pump fault diagnosis based on the continuous hidden markov model (CHMM). Later, the author [2] put forward a new method based on Empirical Mode Decomposition (EMD), and Least Square Support Vector Machine (LS-SVM) for vibration signals analysis of the centrifugal pump which has the non-stationary and non-linearity characteristics of misalignment faults. Application results showed that the proposed method is effective, which can better extract the nonlinear features of the fault and more exactly diagnosis faults.

Farokhzad [3] presented an adaptive network fuzzy inference system (ANFIS) to diagnose the fault type of the pump. The considered pump conditions were healthy, broken impeller, worn impeller, leakage and cavitation. These features are extracted from vibration signals using the FFT technique. According to the result, total classification accuracy was 90.67%. This showed that the system has a great potential to serve as an intelligent fault diagnosis system in real applications.

Nasiri et al [4] applied vibration analysis to detect cavitation in a centrifugal pump using a neural network system. The method provides an intelligent system to be used in condition monitoring of centrifugal pumps.

Wang et al. [5] presented an intelligent diagnosis method for a centrifugal pump system using features derived from vibration signals for misalignment and unbalance monitoring. The diagnosis approaches was derived using wavelet transform, rough sets and a partially linearized neural network (PNN). Reverse Bior wavelet function was used to extract fault features from measured vibration signals and to capture hidden fault information across optimum frequency regions.

Muralidharan et al [6] proposed vibration based fault diagnosis of the monoblock centrifugal pump by wavelet analysis and J48 algorithm. Five classical states were simulated by the authors on the monoblock centrifugal pump such as viz., good, cavitation, bearing fault, impeller fault, both impeller and bearing fault together. Set of wavelet features have been extracted using CWT for different wavelets and classified using J48 algorithm.

Faisal et al [7] applied spectral entropy of the surface vibration and airborne acoustic signals for monitoring cavitation in a centrifugal pump. The spectral entropy was found to be more accurate in presenting the cavitation.

Impeller is the critical component in pump. Continuous running and cavitation in fluids are main destructive causes of impeller damage. The impeller damage leads to other adverse effects such as a drop in the pump head and efficiency, corrosion and undesirable noise/vibration. Therefore, it is important to monitor the condition of impeller.

However, most of these works are based on the statistical information of wideband vibration which is main content of flow turbulence and cavitation. This wideband vibration content is very sensitive to operating environment and the methods may not so stable. This paper presents a new method of fault diagnosis based on Modulated Signal Bispectrum (MSB) analysis of surface vibration. MSB is used to capture the deterministic nonlinear feature of modulation components between fluid pulsations, rotating oscillations of the driving shaft and the impeller for reliable diagnosis.

2. Overview of Pump Vibrations

A centrifugal pump contains the rotating part and the stationary part. The rotating part is composed of a shaft and a pump impeller while the stationary part includes the casing, bearing, electric motor and an associated cooling fan. Based on the working process, the pump vibration sources can be categorized into two types as mechanical and hydraulic sources. Mechanical sources are caused by vibration of unbalanced rotating masses and friction in bearing and seals. The hydraulic sources are due to fluid flow perturbation in the pump and interaction between the rotor blades and stationary component such as the volute tongue or guide vanes[8].

2.1 Mechanical Vibrations Sources

1) Motor and shaft

When the motor in the hydraulic system is rotating at a high speed, the rotating part imbalance can result in periodic unbalanced force and incentive mechanical vibration. The shaft vibration results from the displacement of its shaft from its neutral position due to some external forces generated when the shaft rotates. The shaft vibration frequency is equal to motor rotation frequency.

2) Coupling

Coupling the processing precision and the connection assembly precision, determines the pump shaft and a prime mover driven shaft coaxial degree. If this value is out of tolerance, vibration will be generated.

3) Pipeline and Tank

Pipeline and tank are not the source of vibration. The vibration is influenced by other components, such as pressure and flow pulsation, mechanical vibration and so on. When natural frequencies and vibration frequency of the pipeline and tank is same, then resonance occurs, resulting in strong vibration. Especially when the pipeline is too slender or meticulous and direction changes to a great extent, more easily to cause vibration [9].

2.2 Hydraulic Vibrations Sources

In a pump, vibration is caused by the interaction between the rotating pump impeller and the stationary parts of the pump such as the volute and the diffuser vanes. Also, vibration is caused by the interaction between the impeller vanes and the fluid being pumped.

1) Vane passing frequency

Similar to gear mesh frequency definition, the impeller mesh frequency calculated via Eq. (1).

$$f_{vp} = N_{vp} \times f_r \tag{1}$$

Where, f_{vp} impeller mesh frequency, N_{vp} is number of vane in impeller, and f_r is rotational frequency of impeller in Herz.

2) Hydraulic fluid pump

Hydraulic pump is the main noise source in the hydraulic system. Flow pulsation is an inherent characteristic, which is bound to cause the pump pressure pulsation, including piping, and to spread to the whole system, at the same time to generate vibration. In addition, hydraulic pump leakage and pump hysteresis are also important factors of vibration.

3) Hydraulic valve

When fluid passes through the valve port, it acts as a high-speed jet, and then partial pressure decreased sharply, which leads to vibration. The overflow valve and a throttle valve are high pressure fluid, which causes shear flow, turbulence or vortex in the jet with the surrounding fluid, resulting in high frequency vibration.

4) Cavitation

During the hydraulic system works; a cavitation phenomenon is easily occurred in hydraulic pump suction port and orifice or narrow gap. When cavitation occurs, the fluids with bubbles are formed and flowed into a high-pressure zone, which will produce bigger local instantaneous burst, pressure fluctuation, making the system produce vibration. Cavitation also caused normal volume drop and resulted in poor performance of slow motion components.

5) Turbulent flow and vortex

Due to high flow velocity, the liquid flow will be in the turbulent state and generates a local eddy when flow cross section mutation. While turbulent flow and vortex appear, fluid particle motion, mutual impact, and interaction with the pump, pipeline, valve body wall or other interactions will produce vibration [9].

2.3 Vibration Characteristics

Based on the natures of vibration sources, the content of vibration will includes both a broadband noise and a number of discrete frequency peaks. The broadband content is due to pressure fluctuations generated by flow turbulence, viscous forces, boundary-layer vortex shedding, boundary-layer interaction between a higher velocity and lower velocity region of the process fluid, and by vortices generated in the clearances between the rotor of the centrifugal pump and the adjacent stationary part of the casing. Turbulent noise depends strongly on the flow conditions. If the pump operates at the design operation (the operating point at which a maximum proportion of energy is transferred to move the process fluid), it will have a minimum value. For off-design in the case of flow rates less than the design flow rate additional hydraulic noise is created due to internal recirculation in the suction and discharge areas of the pump impeller and the overall noise of the pump increases. For off-design when flow rates more than the design flow rate boundary-layer vortex shedding increases, flow turbulence increases and additional hydraulic noise is generated [7].

On the other hand, the discrete component characteristics present within the overall spectrum are mainly due to the interaction of the rotor vanes with nearby stationary objects such as the volute tongue and periodicities in the flow due to the discrete nature of the pump's rotor blades. These two mechanisms generate discrete components at the rotational frequency f_r and/or blade passage frequency f_{vp} of the pump and their higher harmonics. Moreover, the shaft frequency will modulate the van passing frequency to cause nonlinear vibration responses. Obviously, the modulation effect will be changed when faults happen of impellers because of the changes of the interaction between van tips and the stationary collectors. Based on these understandings, a deterministic information based diagnosis method can be developed by characterising the modulation process.

3. Modulation Signal Bispectrum

The bispectrum, Fourier transform of the third-order cumulant, is a statistic used to suppress Gaussian noise or detect nonlinear interactions. However, conventional bispectrum is not adequate to describe modulation signals. To overcome this disadvantage, a MSB was proposed in [10, 11]. In this method, the constant phase between the two sidebands of modulated signal is considered in the form of Eq.(2):

$$B_{MS}(f_1, f_2) = E\left\langle X(f_2 + f_1)X(f_2 - f_1)X^*(f_2)X^*(f_2)\right\rangle \tag{2}$$

where f_2 is the frequency of carrier signal and f_1 is of modulated signal, $X(f_2)$ is Fourier transform of the carrier and $X^*(f_2)$ is conjugate of $X(f_2)$. The magnitude and phase of MSB can be expressed as Eq. (3) and (4).

$$A_{MS}(f_1, f_2) = E\left\langle \left|X(f_2 + f_1)\right|\left|X(f_2 - f_1)\right|\left|X^*(f_2)\right|\left|X^*(f_2)\right|\right\rangle \tag{3}$$

$$\phi_{MS}(f_1, f_2) = \phi(f_2 + f_1) + \phi(f_2 - f_1) - \left|\phi(f_2)\right| - \left|\phi(f_2)\right| \tag{4}$$

It takes into account both $(f_2 - f_1)$ and $(f_2 + f_1)$ simultaneously in Eq. (2) for measuring the nonlinear effects of modulation signals. If $(f_2 - f_1)$ and $(f_2 + f_1)$ are both due to the nonlinear effect between $(f_2 - f_1)$ and $(f_2 + f_1)$, there will be a bispectral peak at bifrequency $B_{MS}(f_1, f_2)$ [12]. On the other hand, if these components are not coupled but have random distribution the magnitude of MSB will be close to nil. In this way it allows the wideband noise in pump vibration signals to be suppressed effectively so that the discrete components can be obtained more accurately.

To measure the degree of coupling between three components, a modulation signal bicoherence can be used and calculated by Eq. (6).

$$b_{MS}^2(f_1, f_2) = \frac{\left|B_{MS}(f_1, f_2)\right|^2}{E\left\langle \left|X(f_2)X(f_2)X^*(f_2)X^*(f_2)\right|^2\right\rangle E\left\langle \left|X(f_2 + f_1)X(f_2 - f_1)\right|^2\right\rangle} \tag{5}$$

In addition it can be also seen that for the case of $f_1 = 0$, the power spectrum can be obtained by Eq. (6).

$$PS(f_2) = \sqrt{B_{MS}(0, f_2)} = \sqrt{E\left\langle X(f_2)X^*(f_2)X(f_2)X^*(f_2)\right\rangle} \tag{6}$$

As shown in Eq.(6), the phase of power spectrum for any components is nil and thus it is not possible to suppress random noise by averaging operation..

4. Experimental setup and facility

Figure 1 shows schematic diagram of the test rig used in this experimental work. Figure 2 displays a photo of the test rig. With the layout of flow circuitry, the centrifugal pump can delivery 250 l/min of water under a pressure of 10bar when the driving motor operates at a rated speed of

2900rpm. As shown in the Figure 1, the discharge flow can be adjusted by the discharge control valve to test the pump under different head and low rate, allowing its vibro-acoustics characteristics to be examined over its full operating range.

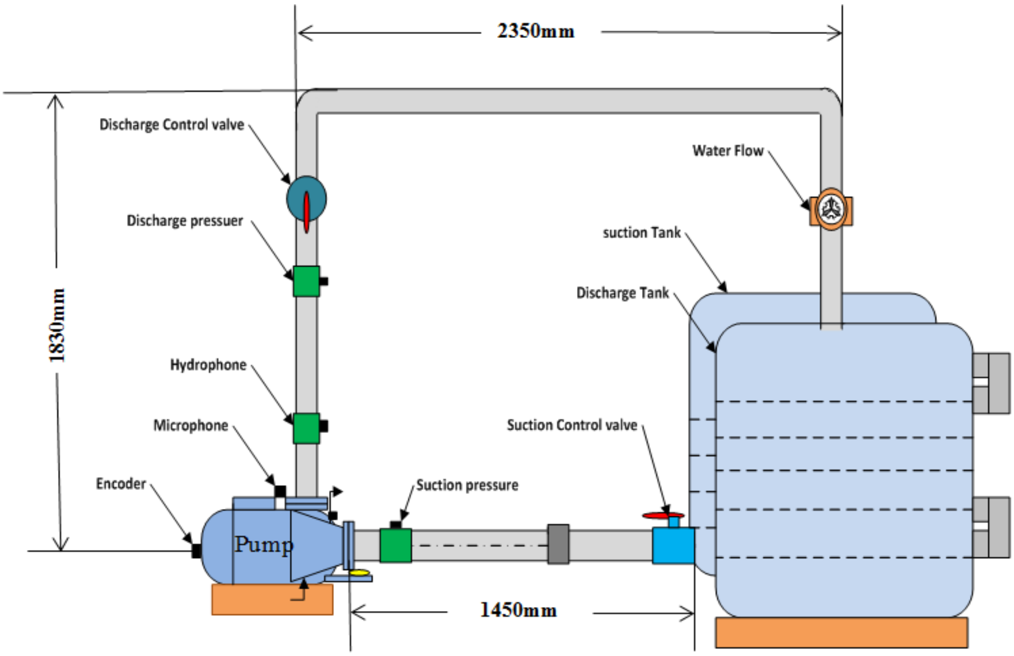

Figure 1 The schematic diagram of the experimental rig

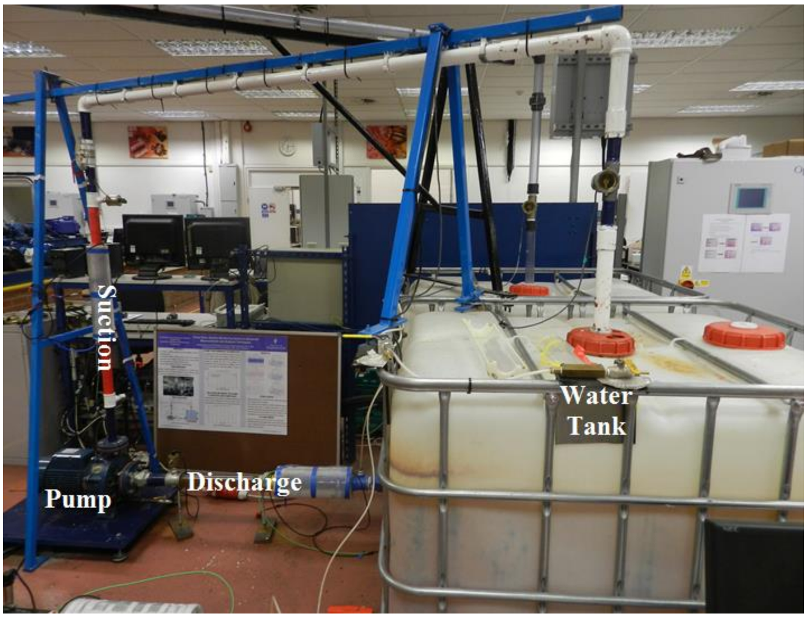

Figure 2 Photo of the pump test rig

The experiment was carried out based on a same pump casing but three different impellers. The first impeller is a healthy one whereas the second and third have inlet vane fault and exit vane fault respectively. As illustrated in Figure 3, the fault of inlet defects was induced to the second impeller by removing a small portion of vane tips on the edge close to the inlet. In the same way the exit fault was created on vane edges of the exit side. These faults are typical erosion modes reported in previous studies.

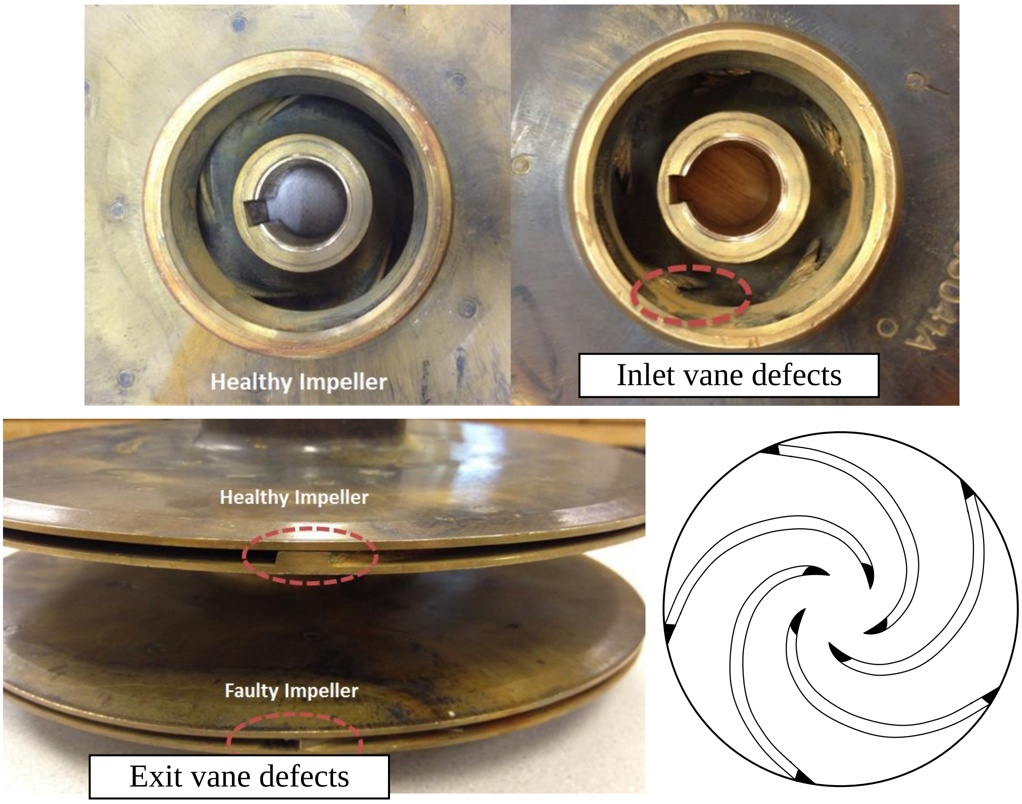

Figure 3 The healthy and faulty impellers

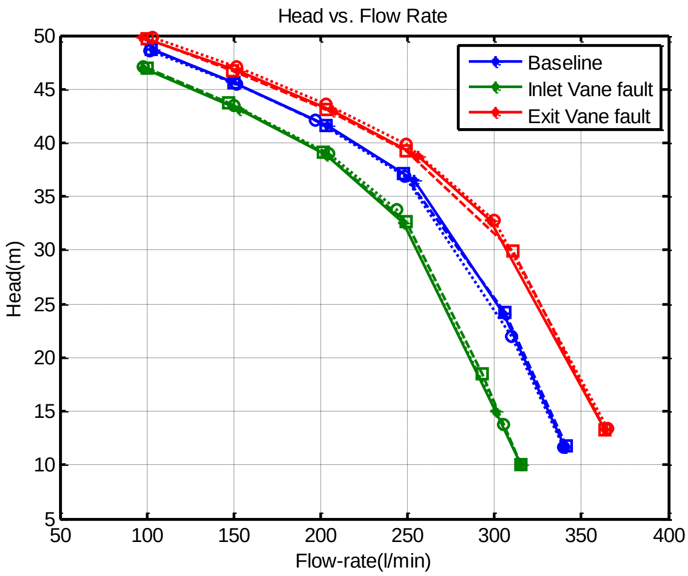

Figure 4 The change of pump performance

During tests, vibration from an accelerometer on the pump casing was collected at a 96kHz sampling rate and 24bit rate. In addition pump performance parameters including flow rate discharge head and motor speed were also measured. Each impeller was installed into the casing in turn and tested at six successive flow rates: 100, 150, 200, 250, 300, and 350 (l/min). In addition, the test was repeated three times for obtaining consistent datasets and reliable comparisons. These multiple test datasets and operating setting will help to understand the vibration characteristics and develop more reliable diagnostic features.

Figure 4 shows the differences of main performance curves for three cases. It can be seen that the inlet defect degrades the performance, which is expected. Surprisingly, the exit vane defect has led to an increase of the performance. It can be understood that the original design may not optimal and remove of the vane tip may improve the main performance. Nevertheless, these two faults have changed the optimal operation. It is expected that this change can be diagnosed from vibration signals measured the externally.

5. Results and Discussion

To examine the performance of vibration based impeller diagnosis, the collected signals are analysed by the MSB approach for finding effective diagnostic features. In addition, results from power spectrum are also calculated using Eq.(7) to benchmark the understandings made in section 2 and 3.

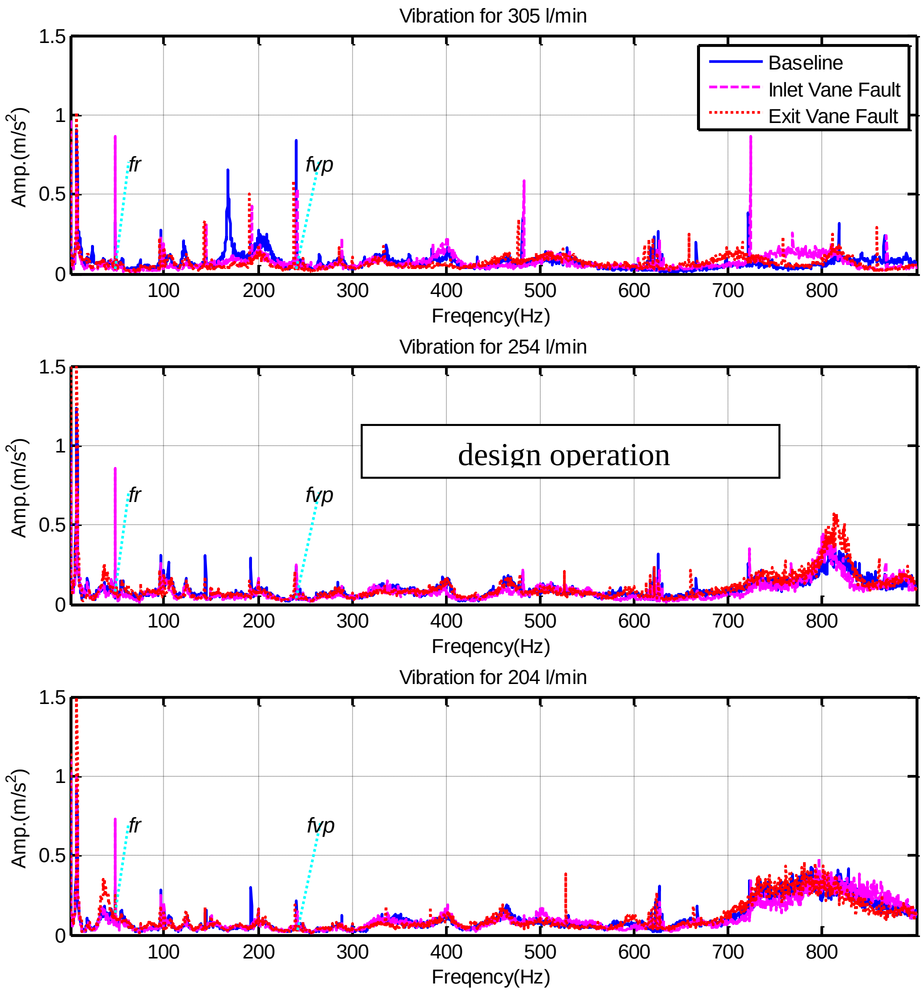

Figure 5 Vibration signals in the frequency domain

5.1 Diagnosis by Spectrum

Figure 5 shows vibration spectra under three typical flow rates and different impeller cases tested. It can be seen that the spectrum have two distinctive components as expected. One is the discrete tone components which are more distinctive in the low frequency range, and the other is the continuous contents which exhibit wideband over the full frequency range. The former is due to mainly the mechanical excitations and propeller induced flow pulsation whereas the latter is mainly due to random excitations including cavitation and turbulence effects. These show that the vibrations signals contains the information of all different sources.

In addition the spectral amplitudes of the discrete components including the van-passing frequency (245Hz), shaft rotating frequency (49Hz) and their harmonics increases with flow rates, showing that mechanical and flow pulsating sources are influenced more by flow velocity or less dampened by the increase of fluid pressure(head). On the other hand, the wideband continuous contents exhibit an adverse change with flow velocity approximately or increase with the fluid pressure.

Moreover, the discrete components show clearer differences between the three impeller cases. However, the continuous contents show less difference. In particular the patterns of continues contents in the frequency range from 600Hz to 100Hz are nearly the same for three cases. Therefore, the low discrete components are focused on for building diagnostic feature.

Figure 6 presents the spectral amplitudes which are averaged over the first 4 harmonics of shaft rotating frequency and the first vane passing frequency. It shows that the amplitudes show less change with flow rates but allows the inlet vane fault to be differentiated fully. However, because of the influences of the wideband noise the exit vane problem can be diagnosed marginally when the flow rate is high.

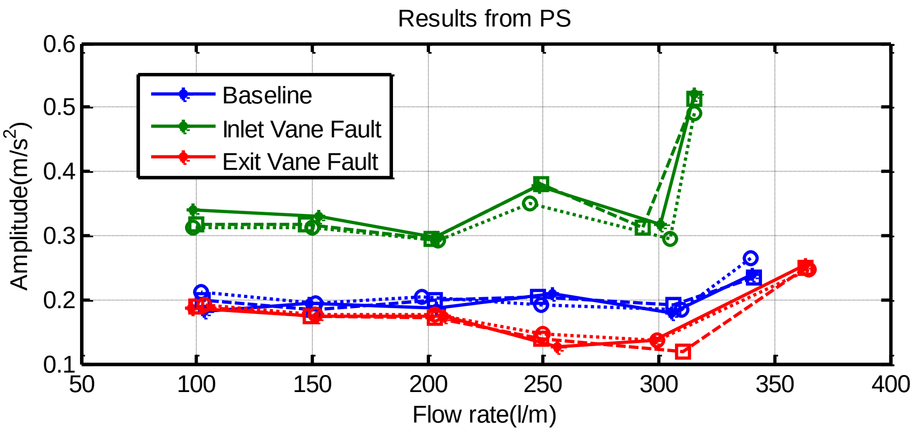

Figure 6 The average amplitudes of discreet components

5.2 Diagnosis by MSB

To improve the diagnosis performance the MSB is applied to suppress the wideband noise and hence to enhance the discrete components. Figure 7 representative of MSB in the low frequency range. The MSB magnitude results of the three graphs of top row show less noise contamination for all three cases. Especially, their nonlinear coupling can be further identified by the corresponding MSB coherences in the three graphs of bottom. In addition, both results show distinctive differences between three cases in that the inlet vane fault causes higher peaks because of higher mechanical and hydraulic pulses whereas the exit vane induces smaller pulses and hence lower MSB peaks.

By extracting and averaging MSB peaks in the low frequency range according to Eq. (8).

$$A_B = \frac{1}{4k^2} \sum_{j=m-k}^{m+k} \sum_{i=n-k}^{n+k} A_{ij} \tag{8}$$

Where (m, n) is the index of the MSB peak position, k=2 is the number of the spectral lines around peak (m, n). The diagnostic features are extracted as shown in Figure (8). It shows that the exit vane fault can be separated from the healthy case with more distinctively, compared with the results from power spectrum. Moreover, it is consistent with the changes of the performance characteristics. As the flow pressure is lower the vibration goes higher for the inlet vane fault and vice versa for the exit vane fault.

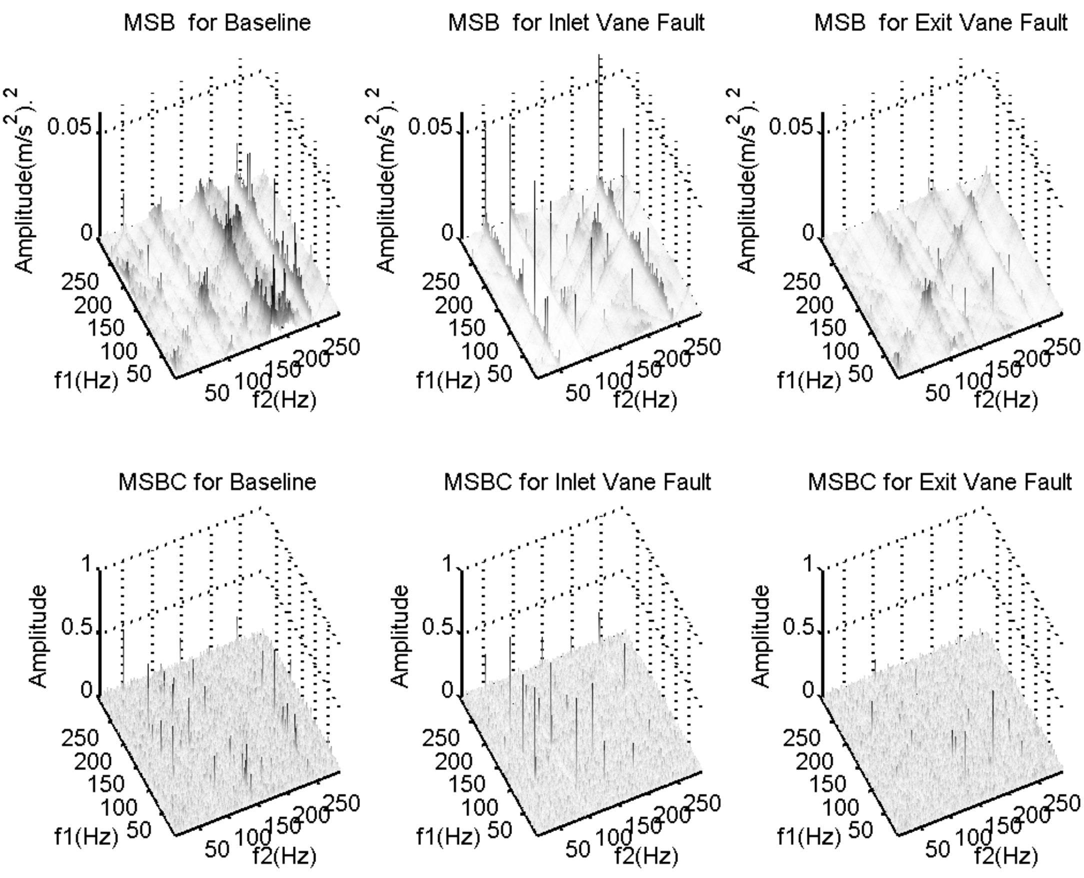

Figure 7 MSB and MSBC of vibration signals for impeller different cases at flow rate 305 l/min.

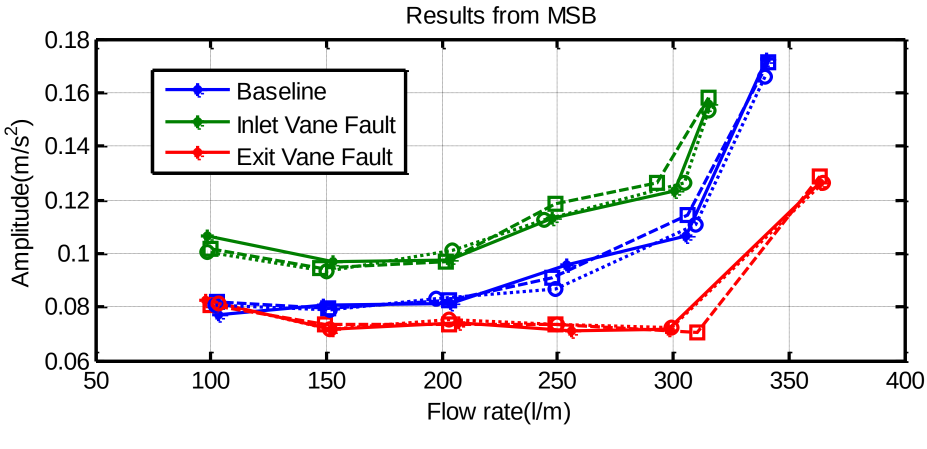

Figure 8 Fault diagnosis based on MSB analysis

6. Conclusion

Vibration signals consist of two contents. The discrete content from mechanical and hydraulic pulsations is more deterministic whereas the wideband content from flow turbulences and cavitation is more random in nature. In this paper, a new method of diagnosing faults occurring pump impellers is proposed based on MSB analysis of vibration signals. MSB allows the spectral amplitude due to pulsations to be estimated more accurately because its capability of wideband noise suppression. Experimental results show that the proposed diagnostic feature, which is obtained by averaging MSB peaks in low frequency range, can make good differentiation of the inlet vane defect and the exit vane fault from the healthy impeller, demonstrating that the proposed method is effective.

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