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*Research Article*

# Detection of Early Faults in Rotating Machinery Based on Wavelet Analysis

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This paper explores the application of wavelet analysis for the detection of early changes in rotor dynamics caused by common machinery faults, namely, rotor unbalance and minor blade rubbing conditions. In this paper, the time synchronised wavelet analysis method was formulated and its effectiveness to detect machinery faults at the early stage was evaluated based on signal simulation and experimental study. The proposed method provides a more standardised approach to visualise the current state of rotor dynamics of a rotating machinery by taking into account the effects of time shift, wavelet edge distortion, and system noise suppression. The experimental results showed that this method is able to reveal subtle changes of the vibration signal characteristics in both the frequency content distribution and the amplitude distortion caused by minor rotor unbalance and blade rubbing conditions. Besides, this method also appeared to be an effective tool to diagnose and to discriminate the different types of machinery faults based on the unique pattern of the wavelet contours. This study shows that the proposed wavelet analysis method is promising to reveal machinery faults at early stage as compared to vibration spectrum analysis.

## 1. Introduction

In machinery condition monitoring, a successful fault detection at the early stage is of paramount importance as most of the catastrophic machinery failures are caused by undetected minute faults that are aggravated over time. To date, vibration spectrum analysis is effectively used to detect sizable machinery faults such as substantial rotor unbalance and misalignment. On the other hand, this method is often found to be less effective to detect machinery faults at the early stage, as the vibration responses caused by minute faults are so subtle that it is often obscured by other more prominent frequency components in the vibration spectrum. Moreover, some machinery faults at the early stage also known to produce transient signals, which are the most important part of a signal to indicate the presence of the faults, if any. However, these signals are often undetectable using vibration spectrum analysis as well. Therefore, to overcome this shortfall, time-frequency analysis methods is often used. Over the years, wavelet analysis (a time-frequency analysis method) is often employed for machinery condition monitoring application mainly to analyse transient and nonstationary signals. Peng and Chu [1] presented a comprehensive review on the application of the wavelet analysis in machinery fault diagnosis. They summarised that wavelet analysis is noted to be widely employed for time-frequency analysis of signals, fault feature extraction, singularity detection, denoising, and extraction of weak signals. One of the prominent application of wavelet analysis for machinery condition monitoring is to detect changes of rotor dynamics due to cracks in a rotor system. Zou and Chen [2] made a comparative study on cracked rotor by using Wigner-Ville distribution method and wavelet analysis. The results of both time-frequency analysis methods were shown to be unique and thus can be used as a criteria to identify cracks in rotor system. Sekhar [3] studied the vibration responses of a cracked rotor system during runup stage using continuous wavelet transforms (CWTs). CWT was found to be capable of extracting the crack signals from vibration responses of the cracked rotor when passing through the critical speed. Other researches in this area of study are such as Prabhakar et al. [4], Zou et al. [5], Sekhar [6], and Darpe [7]. Besides this, wavelet analysis is also widely used to study the vibration responses of rotor rubbing. Peng et al. [8] investigated the application of wavelet scalogram and reassigned wavelet scalogram in detecting the impact signals caused by rubbing. They observed that when rubbing occurred, an increase of magnitudes can be observed not only at the fundamental rotational frequency but also at high frequency regions. Peng et al. [9] reported a hybrid method of acoustic emission and wavelet analysis to determine the locations of rubbing in the rotor system. Wang and Chu [10] used wavelet analysis and its phase maps to study the nonlinear behaviours of rubbing that occurred in rotor systems. Al-Badour et al. [11] investigated stator-to-blade rubbing phenomena of a running machine and it was found that the combination of continuous wavelet and wavelet packet transforms provides a better means to monitor vibration signal induced by rubbing. Ma et al. [12] studied two different phenomena of rotor rubbing, which are rotor rub coupled with crack and bearing rub coupled with oil-film instability. It was found that by combining spectrum cascade, reassigned wavelet scalogram, rotor trajectory, and frequency spectrum, some novel fault features useful for rubbing detection can be discovered from the vibration signals measured in rotor runup and rundown. Patel and Darpe [13] investigated the vibration response of a rotor during runup and it was found that the transient vibration signal of runup can be used as an early indicator of minor rotor rub. In addition, a fault features extraction method for rotor rubbing detection based on load identification and impact response was also studied by Li et al. [14]. Beside this, the authors [15] also conducted a study on the feasibility of wavelet analysis in detecting loose blades in a rotor system based on the minute impact signals measured during rundown process.

Although the effectiveness of wavelet analysis to detect these machinery faults is extensively demonstrated in these literatures, the specific application of wavelet analysis to detect minute machinery faults at the early stage is not sufficiently discussed and reported. Therefore, the objectives of this study is to formulate a new wavelet analysis method that could be employed to reveal common machinery faults at the early stage.

## 2. Formulation of Time Synchronised Wavelet Analysis

Wavelet analysis is a very versatile signal analysis tool. As of today, there are many variations of wavelet analysis algorithms which could be deployed to analyze the signals in hand (e.g., continuous wavelet analysis, discrete wavelet analysis, and stationary wavelet analysis). Therefore, a meaningful comparison of wavelet analysis results is only achievable if the same wavelet analysis algorithm is being used to analyze the signals. Besides, unlike vibration spectrum analysis, an effective comparison of wavelet analysis results entails some signal preprocessing steps to be undertaken. These includes the reposition of signals prior to wavelet transform (so that each signal could start and stop at the same position in time to avoid any misinterpretation of results due to time-shift effect), the steps to suppress random system noises (as contaminated wavelet results are much more difficult to interpret), and the ways to address distortion of wavelet results at the edge of a signal. In view of this, the time synchronised wavelet analysis is formulated in this study to address these issues. The following outlines the signal processing steps required.

(i) In order to avoid misinterpretation of wavelet results due to time-shift effect, vibration and tachometer signals are simultaneously measured during steady state operating condition (see Figure 1). The tachometer signal provides the necessary guideline to identify a specific point in the time waveforms. Numerous segments of time signals are extracted from the continuous vibration signals using tachometer signal as the guideline and in accordance with the timeframe of two complete rotational cycles. This practice of signal segmentation is found to be effective to eliminate random system noises using synchronous time averaging process even with relatively shorter length of signals. For example, with just 1 s of time signal, it is sufficient to produce as many as 25 number of time segments (for a machine operating at 50 Hz), which could be input for time synchronous averaging process to minimise random system noises. In this study, the de-noised time synchronised signals is obtained via the above operation and to cater for subsequent wavelet transform.

(ii) Continuous wavelet analysis is then applied onto the time synchronised signal to produce the time synchronised wavelet analysis. As there are numerous wavelet families available for wavelet analysis of a signal, hence the selection of the mother wavelet families for signal analysis depends on its characteristics of that family such as the shape of the wavelet: symmetry, the number of vanishing moments, and the regularity. The wavelet family is important to the pattern of the wavelet map representing the signal in hand. Coiflet (level 5) wavelet was chosen for wavelet analysis of the experimental signal based on the fact that Coiflet (level 5) wavelet is fairly symmetrical and regular in shape (see Figure 2). Wavelet map plotted with this wavelet was also found to be fairly symmetrical and smooth for the display of the vibration signals measured from the experiment. The wavelet analysis is then carried out from scale 1 to 50 at a scale resolution of 0.1. Subsequently, in order to avoid misinterpretation of wavelet results due to edge distortion effect, the practice of dividing the signals in accordance with two complete rotational cycle is also found handy. The minimum edge distortion region could be seen in the middle of the wavelet display (see Figure 3) which provides undistorted information for more than one cycle of rotation.

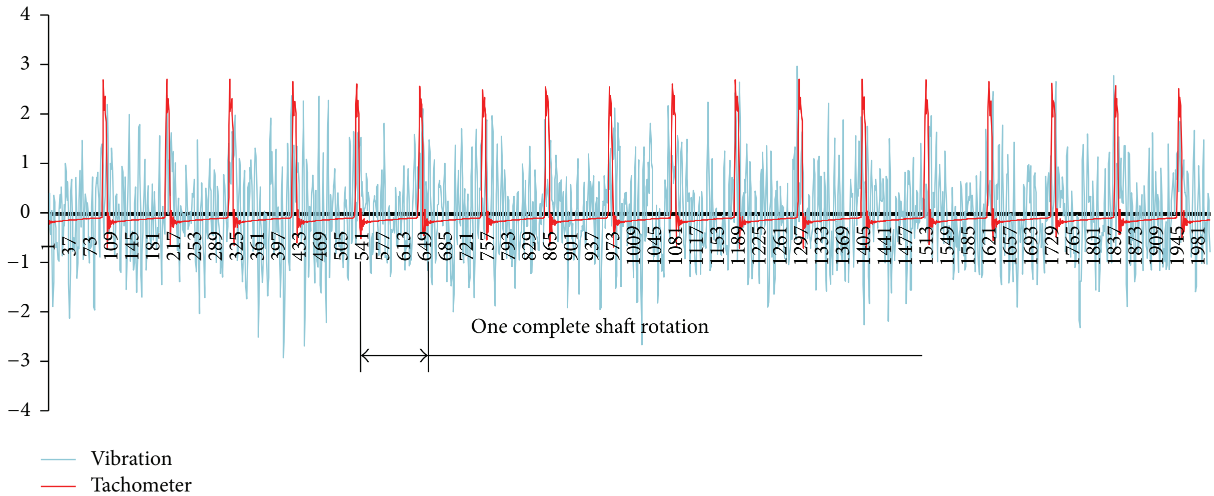



Figure 1: Vibration and tachometer signals in collation.

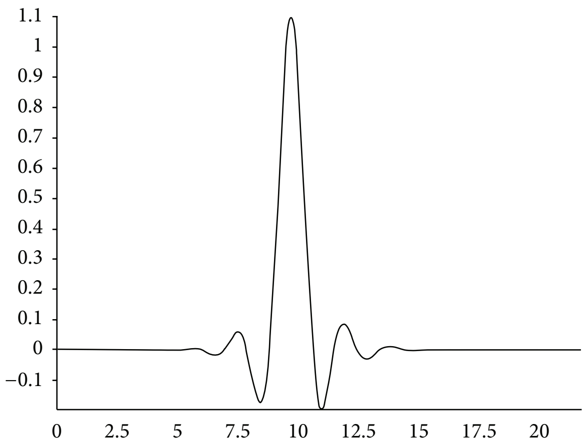


Figure 2: Coiflet 5 scaling function.

(iii) Finally, in order to simplify and to facilitate the interpretation of wavelet results, only positive wavelet coefficients are displayed in time synchronised wavelet analysis. In short, the time synchronised wavelet analysis provides a timefrequency view of the current rotor dynamics state of a rotating machinery by taking into account the effects of time-shift, edge distortion, and system noise suppression.

## 3. Signal Simulation Study

The effectiveness of the time synchronised wavelet analysis to detect changes in signals (i.e., frequency content alteration and amplitude distortion) is evaluated in this section. Various test signals were produced in this study to simulate and to approximate the likely signals of a rotor-bladed system under healthy and faulty conditions. The test signals were generated based on (1), which includes various basic frequencies of a rotor-bladed system such as the operating frequency (1x)

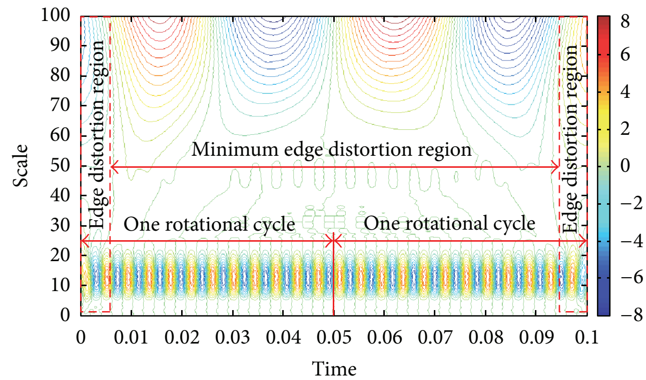



Figure 3: Time synchronised wavelet analysis.

and its second harmonics (2x), and the blade pass frequency (BPF). BPF is the frequency generated when rotating blades pass through a stationary component such as a casing and its frequency is calculated by multiplying the operating frequency with the number of blades in the rotor (operating frequency × no. of blades):

$$S(n) = A1 \sin(2\pi n \times F1) + A2 \sin(2\pi n \times F2) + A3 \sin(2\pi n \times F3), \quad (1)$$

where $S(n)$ is the generated test signals. $A1$, $A2$, and $A3$ are the amplitude of the signals for 1x, 2x, and BPF, respectively. And $F1$, $F2$, and $F3$ denote the frequency of 1x, 2x, and BPF, respectively. Table 1 tabulates the parameters used to generate the four test signals in relation to its simulated condition. The test signals are also illustrated in Figure 4.

*3.1. Results and Discussion of Signal Simulation Study.* Figures 5(a) and 5(e) illustrate the results of wavelet analysis and frequency spectrum for signal S1 (baseline condition), respectively. It could be noted that the two frequency components

Table 1: Signal simulation for baseline and faulty conditions.

| Number | Simulated signal components | Signal parameters | Simulated conditions |
|---|---|---|---|
| S1 | 1x and BPF | $A1 = 1$; $A2 = 0$; $A3 = 1$<br>$F1 = 20$; $F2 = 40$; $F3 = 240$ | Baseline (healthy) condition of a rotor-bladed system |
| S2 | 1x, 2x (minor), and BPF | $A1 = 1$; $A2 = 0.05$; $A3 = 1$<br>$F1 = 20$; $F2 = 40$; $F3 = 240$ | Minor misalignment of a rotor-bladed system |
| S3 | 1x, 2x (severe), and BPF | $A1 = 1$; $A2 = 1$; $A3 = 1$<br>$F1 = 20$; $F2 = 40$; $F3 = 240$ | Severe misalignment of a rotor-bladed system |
| S4 | 1x and distorted BPF as highlighted in Figure 4(d) | $A1 = 1$; $A2 = 0$; $A3 = 1$<br>$F1 = 20$; $F2 = 40$; $F3 = 240$<br>For data point ($n$), $70 < n < 76$ and $276 < n < 282$, $S(n) = S(n) + 1$ | Distorted BPF caused by blade creep induced rubbing |

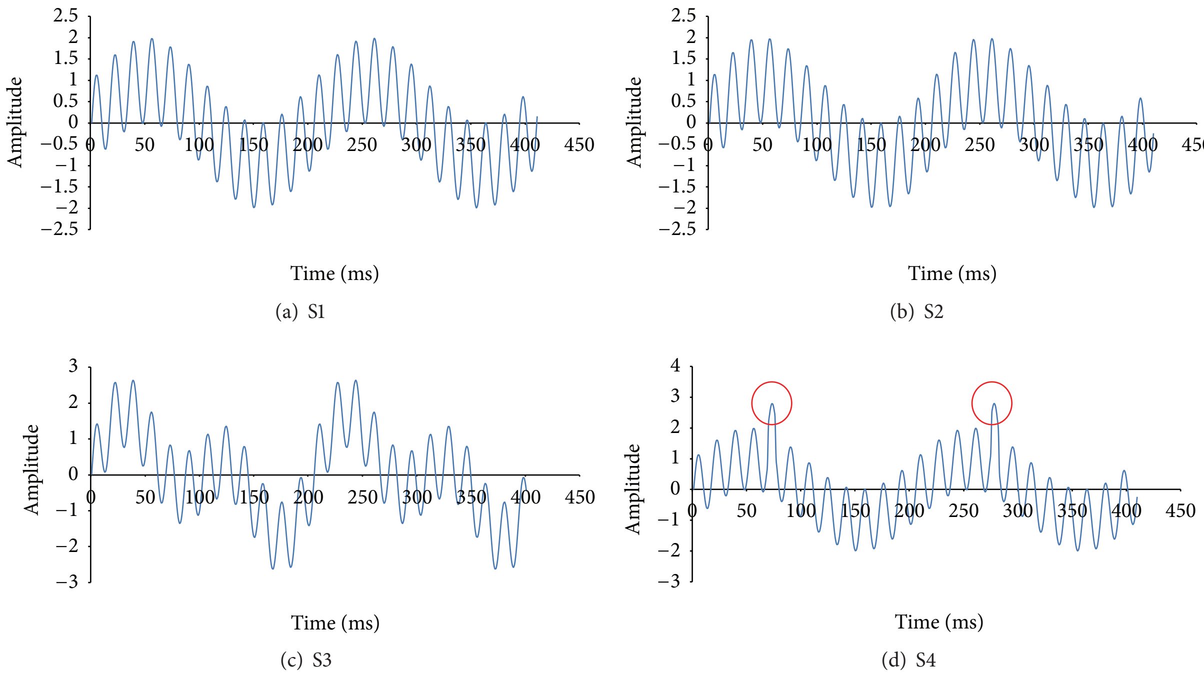



Figure 4: Generated signals for signal simulation study.

of signal S1 are clearly seen in the frequency spectrum. Meanwhile, based on wavelet analysis results, the amplitude fluctuation of 1x component (marked as contours 1 and 2 in Figure 5(a)) and BPF could also be seen located at scale 100 (20 Hz) and scale 15 (240 Hz) of the wavelet display. Subsequently, the result of wavelet analysis and frequency spectrum of signal S2 (minor misalignment) are compared and illustrated in Figures 5(b) and 5(f), respectively. The vibration spectrum of both signals S2 and S1 can be identified based on the minute vibration peak seen on the vibration spectrum plotted in logarithm scale. However, this minute 2x frequency component is barely visible in the frequency spectrum plotted in linear scale as the magnitude of 2x is only 1/100 of the 1x and thus could easily be ignored or overlooked. By contrast, the 2x frequency component could be easily noticed at scale 50 in the wavelet contour (marked as contours 3 and 4 in Figure 5(b)). By extrapolating to real world scenario, this phenomenon could provide a first-hand indication about the presence of minor misalignment condition in the rotor system. Therefore, wavelet analysis is found to be a more effective method to detect early changes of rotor dynamics of a rotor system as compared to frequency analysis. Next, by increasing the amplitude of 2x signal as in signal S3, the 2x frequency peak could clearly be seen in the frequency spectrum (see Figure 5(g)). Similarly, the substantial 2x component could also be traced

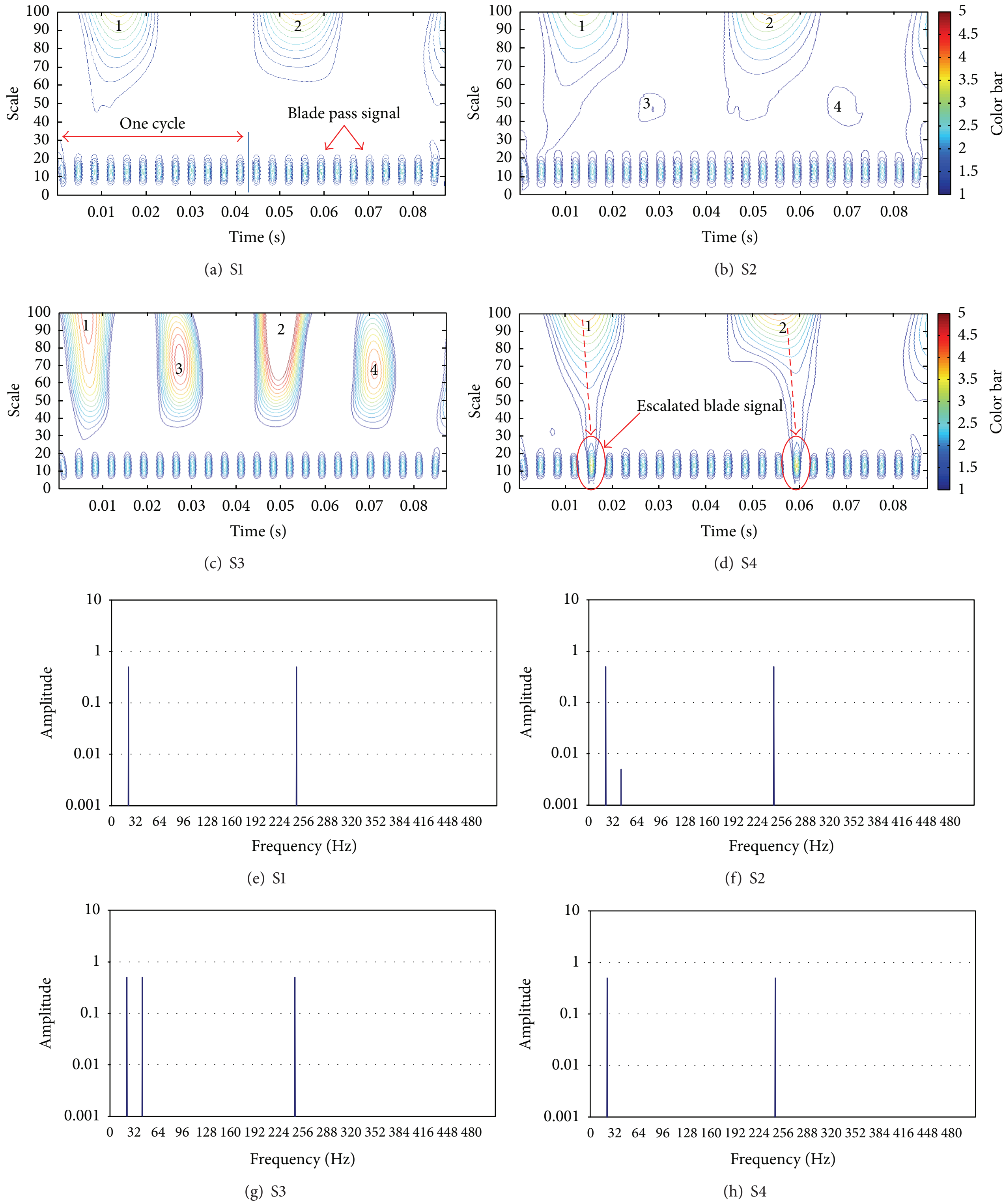
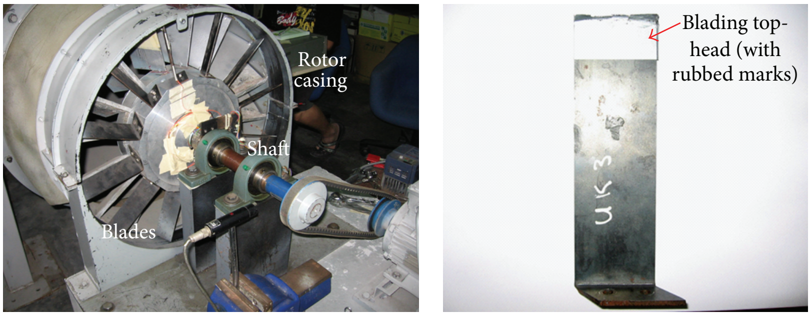



Figure 5: Comparison of results for signal simulation study.

at scale 70 in the wavelet display (marked as contours 3 and 4 in Figure 5(c)). This suggests that for severe misalignment condition, both methods could also be employed to detect the fault. Finally, the results of wavelet analysis and frequency spectrum for signal S4 (distorted BPF) are illustrated in Figures 5(d) and 5(h), respectively. By comparing the frequency spectrum of signal S4 and signal S1, no significant differences are noticeable. Thus, frequency analysis is said to




(a) (b)

Figure 6: Rotor system and rubbing mechanism used for experimental study.

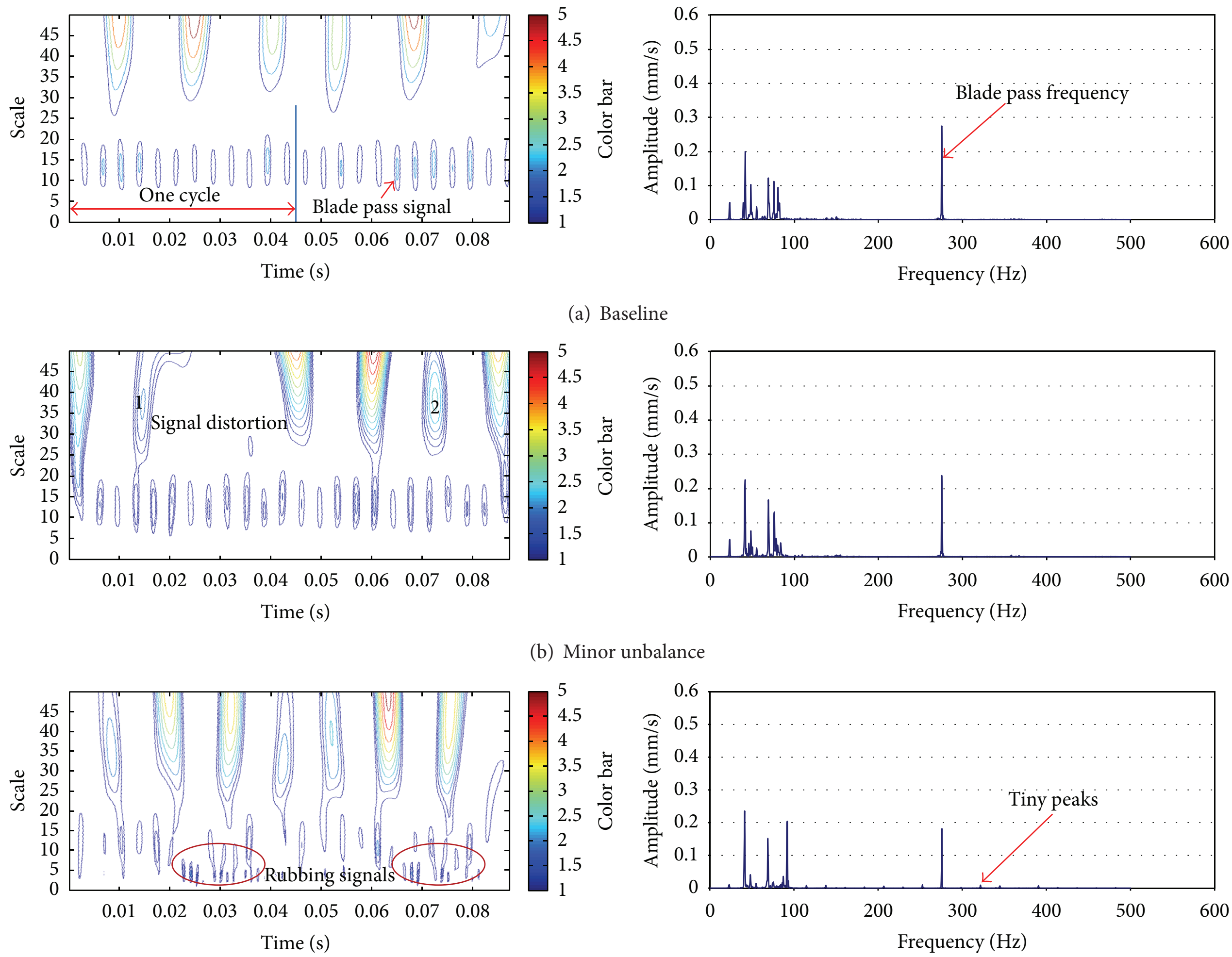
be ineffectual to detect any minor amplitude distortion that is present in a signal. By contrast, the wavelet result of signal S4 clearly indicates the presence of amplitude distortion found at BPF region. The location of distorted signal could easily be identified based on the wavelet contour. On top of that, the instantaneous signal distortion in BPF signal could also observed to affect the contour of the operating frequency. The special relationship between the distorted BPF and the harmonics of operating frequency could be used to detect the occurrence of blade rubbing in the rotor. As a summary, wavelet analysis is found to be a more effective tool to detect any minute changes in the frequency content and the minor amplitude distortion of a signal as compared to frequency analysis method.

## 4. Experimental Study

*4.1. Experimental Setup.* An experimental study was conducted in order to evaluate the effectiveness of the proposed wavelet analysis method to detect early changes in rotor dynamics caused by two different machinery faults, namely, rotor unbalance and blade rubbing. Therefore, an experimental rig consists of a rotor and casing, twelve units of blades, and some experimental control mechanisms was thus fabricated (see Figure 6(a)). The rotor unbalance condition was induced in the experiment by adding different weight of masses to the rotor system. For minor and severe unbalance conditions, masses of 2 g and 8 g of weight were added to the rotor system, respectively. In addition, in order to examine the vibration response of blade rubbing, a component termed as "top-head," which is made of aluminium sheet metal (see Figure 6(b)), was used to extend the blade length and to act as the rubbing medium between the blade and the casing. Blade rubbing was examined in the experiment with two different degrees of rubbing severities, namely, minor rubbing and severe rubbing. The condition of minor rubbing was induced for blade position 6 whereby the top-head was extended to touch lightly onto the casing. Meanwhile, severe blade rubbing was induced for blade positions 8 and 9 with the top-head clearly protruding out of the casing. Therefore in order to fit the protruding top-head into the experiment rig, it has to be bent first. In this experimental study, the operating speed was set at 1500 rpm with vibration signals measured at bearing and upper rotor casing in triaxes.

*4.2. Results and Discussion of Experimental Study*

*4.2.1. Detection of Minor Fault Conditions.* The vibration spectrum and wavelet contour of baseline, minor unbalance, and minor blade rubbing were compared in Figure 7. At a glance, the vibration spectrum of these conditions were observed to be almost similar; although some tiny vibration peaks could be observed in the frequency spectrum of minor blade rubbing condition. However, the changes are so subtle that could therefore be negligible. Subsequently, the wavelet contours of baseline condition and minor faulty conditions were compared. For baseline condition, its wavelet contour was observed to be relatively clean. The periodicity of twelve blades passing pulsations at scale 15 (BPF region) could clearly be observed. Besides, the harmonics of operating frequency could also be seen located at scale 50. For minor unbalance condition, its wavelet contour was observed to be slightly distorted at scale 50. Besides that, additional frequency components at scale 35 (marked as contours 1 and 2) were also noted, which was not present in the baseline condition. These observations provide some information about the changes of rotor dynamics characteristic due to minor unbalance condition. While for minor blade rubbing condition, its wavelet contour was found to have changed accordingly. Firstly, the blade pass signal at scale 15 of wavelet display is observed to be smeared by the rubbing energy. Secondly, some rub marks could also be observed located at scale 5. These phenomena were not present in the wavelet contour of baseline condition; therefore, provides early indicator about the presence of minor blade rubbing. Based on this finding, wavelet analysis was found to be a more effective method to detect minor blade rubbing based on the unique contour of wavelet display as compared to vibration spectrum analysis. This study suggests that wavelet analysis is effective to detect machinery faults at early stage as compared to vibration spectrum analysis.




(a) Baseline

(b) Minor unbalance

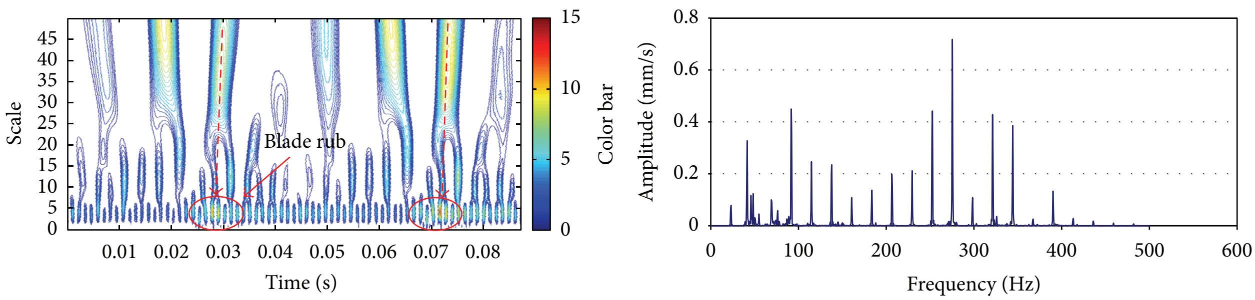
(c) Minor blade rub

Figure 7: Comparison of results for baseline and minor fault conditions.

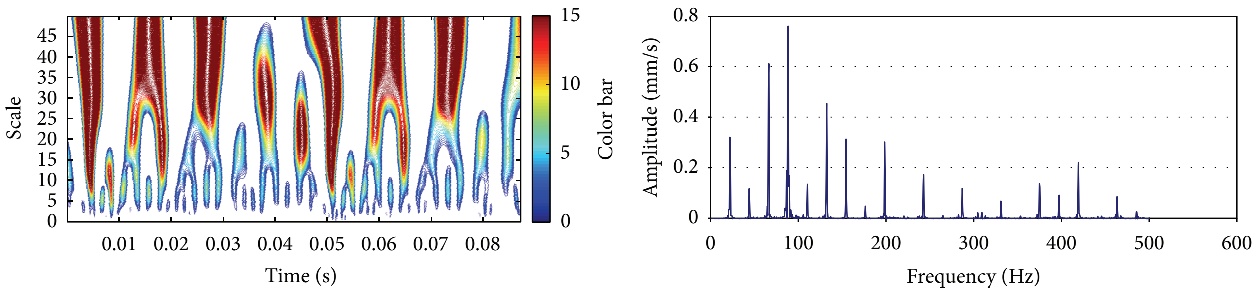
*4.2.2. Fault Diagnosis of Severe Fault Conditions.* Figure 8 compares the vibration spectrum and wavelet contour of severe fault conditions: severe unbalance and severe blade rubbing. The vibration spectrum of these two conditions were observed to be heavily dominated by harmonic peaks of operating frequency. Although its vibration patterns and frequency peaks were different, it is still relatively difficult to differentiate between them. In this case, severe blade rubbing could be wrongly diagnosed as unbalance condition, or vice versa. By contrast, severe blade rubbing could be easily differentiated from severe unbalance condition based on their wavelet contours. For severe blade rubbing, some instantaneous rubbed marks at scale 5 (higher frequency region) could be observed, which also affected the higher scale region (low frequency region) of the wavelet display (see Figure 8(a)). This phenomenon shows close resemblance to the wavelet contour of simulated signal S4 (distorted BPF). Whereas for severe unbalance condition, most of the changes in its wavelet contour were observed to be located at the low frequency regions (scale 35 and below). The differences in wavelet contour for both conditions provided a picture about the mechanism of the faults in the rotor system and thus could be used as the key to differentiate them.

## 5. Conclusion

The time synchronised wavelet analysis method was successfully formulated in this study. The experimental results showed that this method is more effective than vibration spectrum analysis to detect early changes of rotor dynamics caused by minor rotor unbalance and minor blade rubbing conditions. Besides that, this method also appeared to be a viable tool to diagnose and classify severe machinery faults based on the unique contour of the wavelet displays. In addition, the proposed wavelet analysis method also provides a more standardised approach to visualise the current state of rotor dynamics of a rotating machinery by taking into account the effects of time shift, edge distortion, and system noise suppression, which may be applicable for general machinery condition monitoring applications as well.




(a) Severe blade rub




(b) Severe unbalance

Figure 8: Comparison of results for severe fault conditions.

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