Vibration-based Fault Diagnostics of Planetary Gearbox Using Time Synchronous Averaging with Multiple Window Functions

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ABSTRACT

Recently, numerous number of studies have been made to advance TSA for vibration-based diagnostics of planet gears of a planetary gearbox. To increase signal-to-noise ratio of the vibration signals, various narrow-range window functions centered on sensor's position have been developed to capture the instances when the planet gears are adjacent to the sensor. However, TSA with such narrow-range window functions is unable to detect the abnormal signal if it is amplified at outside of the sensor's position due to an unexpected vibration modulation characteristics of the gearbox. This paper proposes a TSA which is robust toward the unexpected vibration modulation characteristics of the gearbox. Multiple narrow-range window functions were employed to perform multiple TSAs rather than employing the sole window function centered on the sensor's position. Condition indicators with regard to every ring gear's teeth were derived, and accumulated for the purpose of condition monitoring. Then, optimal position of the window function was determined to maximize capability to detect signals from the faulty gear. For demonstration of the proposed TSA, test was performed with a 2kW testbed having one-stage planetary gearbox within which a planet gear with artificial fault was assembled.

1. INTRODUCTION

Planetary gearbox is widely used for various large-scale engineering systems such as wind turbines, helicopters and mining machines. However, planetary gearbox frequently suffers from unexpected failures which causes huge amount of operation and maintenance (O&M) cost of the system. Thus, it is necessary to early detect fault of the gearbox to prevent catastrophic failure of the entire system, which also

results in reducing the O&M cost. For this purpose, vibration-based diagnostics techniques have been widely used.

Time synchronous averaging (TSA) enables to minimize noise of vibration signals measured from a gearbox, thus resulting in an effective vibration-based diagnostics of the system with low computational cost (Bechhoefer et al., 2009). However, conventional TSA cannot be used for fault diagnostics of the planetary gearbox because of the following reasons; 1) vibration signal is made by multiple vibration sources including a ring gear, a sun gear, and several planet gears, 2) vibration signal is modulated by the planet gears revolving around the sun gear. For the use of TSA for the planetary gearbox, narrow-range window functions have been employed (McFadden & Howard, 1990, McFadden, 1991, Samuel, Conroy & Pines, 2004, Lewicki, Ehinger & Fetty, 2011). The narrow-range window function is located at the position of the sensor to capture the instances when the planet gears are adjacent to the sensor. This approach enables to focus on the certain meshing condition of interest and to minimize the undesirable effect of revolution of the planet gears.

However, it was reported that the loads carried by the planet gears can vary with several causes such as manufacturing tolerance and excessive radial load (Inalpolat & Kaharman, 2010). In the worst-case scenario, contact with high load between planet gears and the ring gear can be made at the opposite position of the sensor. In this case, narrow-range window function may not detect the abnormal signal that could be amplified at the opposite position of the sensor.

This paper newly proposes a TSA which is robust toward the unexpected vibration modulation characteristics of the planetary gearbox. The proposed method suggests to employ multiple TSAs with multiple window functions rather than a sole window function centered on the sensor's position. The number of window functions was set to be same as the number of teeth of the ring gear. Afterward, condition indicators with regard to every ring gear's teeth were derived

and accumulated. When a typical tooth of the planet gear is failed, condition indicator at certain ring gear's tooth will become out of range of normal condition. Then, optimal position of the window function can be determined to maximize the capability to detect faulty signals in tooth domain. For demonstration of the proposed TSA, tests were performed with a 2kW testbed having one-stage planetary gearbox in which a planet gear with an artificial fault was assembled. Although the proposed diagnostics method requires relatively long computational time compared to the conventional diagnostics method, the demonstration results showed that the proposed method performed quietly well. The remaining parts of the paper are organized as follows. In Section 2, TSA is briefly reviewed. Section 3 introduces a possible vibration modulation characteristics of the planetary gearbox when non-ideal operating condition is made. In addition, TSA with multiple window functions is proposed. And then, demonstration study is presented in Section 4.

2. REVIEW OF TIME SYNCHRONOUS AVERAGING

2.1. Conventional time synchronous averaging (TSA)

A synthesized signal ($v(\theta)$) from a sensor attached to a gearbox can be expressed as (Hochmam & Sadok, 2004):

$$v(t) = S(t) + N(t) + R(t) \qquad (1)$$

where $S(t)$ is the synchronous coherent signal, $N(t)$ is the non-synchronous coherent signal, and $R(t)$ is the non-coherent random signal. In the case of the gearbox, synchronous coherent signal ($S(t)$) is produced by meshing of the gears of interest, and non-synchronous coherent signal $N(t)$ is generated from other vibration sources which are out of interest (e.g. bearings). Non-coherent random signal is Gaussian noise in general. For condition monitoring of a particular gear of interest, it is essential to isolate the synchronous coherent signal from the measured synthesized signal. TSA enables to isolate the synchronous coherent signal by suppressing the non-synchronous coherent signal, and de-noising the non-coherent random signal. Figure 1 illustrates the general procedures of TSA which are made up of two steps. First, the synthesized signal is divided into N segments (e.g., v_i in Figure 1) based on the rotational
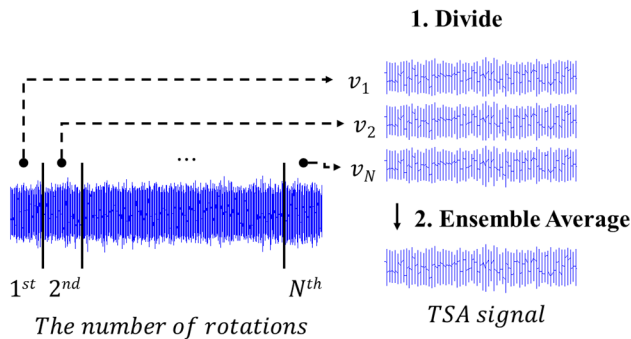
frequency of the gear of interest. For this purpose, resampling of vibration signals should be performed with the help of encoder system. Second, the divided segments are ensemble averaged to make a TSA signal.

Because the non-synchronous coherent signal and the non-coherent random signal follow a Gaussian distribution with a mean of zero, they theoretically converge to zero as the number of segments accumulate. On the other hand, every divided segments have almost identical deterministic vibration signals with almost same phase and magnitude. Thus, a synchronous coherent signal aren't significantly affected by the ensemble average process. The TSA for isolation of the synchronous coherent signal is defined as:

$$S(t) \approx \frac{1}{N} \sum_{i=1}^{N} v_i(t) \qquad (2)$$

where $v_i(\theta)$ is the ith segment corresponding to i^{th} rotation of the gear of interest, and N is the number of segments averaged for TSA.

2.2. Time Synchronous Averaging for Planet Gears

Planetary gearboxes have four main components including a carrier, a ring gear, a sun gear, and multiple planet gears. This paper employed a 2kW testbed with a planetary gearbox which has a sun gear (31 teeth), a ring gear (95 teeth), and three planet gears (31 teeth) as shown in Figure 2. The ring gear is fixed on the gearbox housing and every planet gear revolves around the sun gear. Because vibration sensors are fixed on the gearbox housing, relative distance of the planet gears to the sensors varies. Sensor was attached to the top of the gearbox housing under which tooth number one was assigned to the tooth of the ring gear. At the initial condition of test, tooth number one of the planet gear of interest was set to contact with tooth number one of the ring gear. In addition, position of the inner gears are tracked in real time with the help of a high-resolution encoder system.

Narrow-range window functions have been employed to extract the vibration signals when the planet gear of interest

1. Divide

The number of rotations

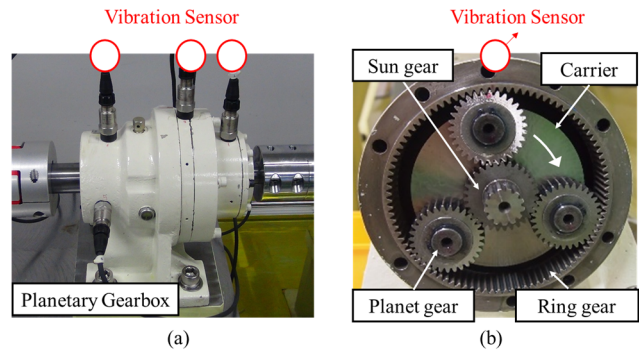Figure 1. Procedures of time synchronous averaging

Figure 2. Planetary gearbox; (a): outside of the gearbox, (b): Inner side of the gearbox
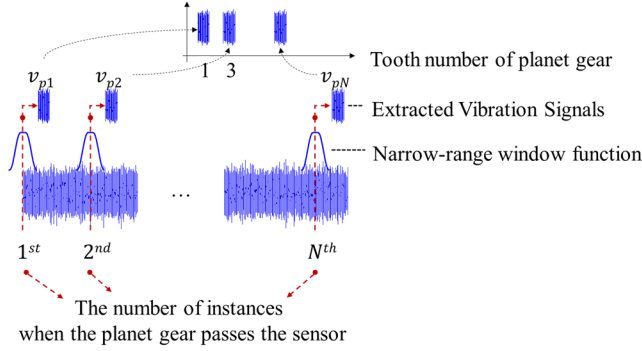
Figure 3. Window function for extraction of vibration signals

is adjacent to the sensor (McFadden et al., 1990). Figure 3 illustrates the procedure of TSA with the narrow-range window function. The narrow-range window function helps remove the noisy vibration signals generated from the other gears which are out of interest. Consequently, the extracted signals with reduced noise can effectively serve as a qualified source for TSA.

For TSA with the narrow range window function, tooth sequence of the planetary gearbox should be considered. Tooth sequence for a planet gear is defined as tooth number of the planet gear that mesh with the ring gear under the sensor. Tooth sequence arises from a feature that N_r (the number of teeth of the ring gear) is non-integer multiple of N_p (the number of teeth of the planet gear). Tooth sequence of the planet gear (T_p) which meshes with the ring gear under the sensor at n^{th} rotation of the carrier can be identified as:

$$T_p(n_c) = \mod(n_c N_r, N_p) + 1 \qquad (3)$$

where n_c is the number of carrier rotation, N_r is the number of ring gear's teeth, N_p is the number of planet gear's teeth.

Figure 3 illustrates an example where it is assumed that v_{p1} was generated by tooth number one of the planet gear whereas v_{p2} was generated by tooth number three of the planet gear. In this case, every extracted signal should be transported to the appropriate position of the planet gear's tooth domain as shown in upper side of Figure 3. After transforming all of the extracted vibration signals, TSA can be performed to isolate the synchronous coherent signal which is generated by the planet gear of interest.

2.3. Extraction of Condition Indicator

For quantitative fault diagnostics of the gearbox, various condition indicators (CIs) can be defined using the signals processed with the TSA. Although several attempts were made to find a best CI for condition monitoring of a specific engineering system, consideration of various CIs is valuable if best CI is not identified for the given system. This paper employed three kinds of CIs (i.e. *SER* (Sheng, 2012), *FM4* (Stewart, 1977) and *M6A* (Martin, 1989)) which can be

defined as:

$$SER = \frac{\sum_{i=1}^{6}\left(A\left(f_{s(i)}\right)\right)}{A\left(f_1\right)} \qquad (4)$$

$$FM4 = \frac{\dfrac{1}{N}\sum_{i=1}^{N}\left(DIF(i) - \mu_{DIF}\right)^4}{\left[\dfrac{1}{N}\sum_{i=1}^{N}(DIF(i) - \mu_{DIF})^2\right]^2} \qquad (5)$$

$$M6A = \frac{\dfrac{1}{N}\sum_{i=1}^{N}\left(DIF(i) - \mu_{DIF}\right)^6}{\left[\dfrac{1}{N}\sum_{i=1}^{N}(DIF(i) - \mu_{DIF})^2\right]^3} \qquad (6)$$

where $A(f_1)$ and $A(f_{s(i)})$ denote amplitude of vibration signal at fundamental frequency and i^{th} sideband of the fundamental frequency respectively, and μ_{DIF} stands for mean of *DIF*. *DIF* denotes a difference signal which can be defined by excluding fundamental gear mesh frequency and their harmonics along with their sidebands (Samuel & Pines, 2005). Because resampling was performed before TSA processing, fundamental frequency and their harmonics are integer numbers represented in order domain.

3. TSA WITH MULTIPLE WINDOW FUNCTIONS

Section 2 described TSA which was especially developed for the diagnostics of the planet gears. Overall procedures for the advanced TSA was based on an assumption that the vibration signal is modulated to have an enlarged magnitude when the planet gears are passing the vibration sensor. Consequently, it was believed the faulty signal can be effectively captured when the faulty tooth of the planet gear meshes with the ring gear around the sensor. This section investigates a planetary gearbox having an unexpected vibration modulation characteristics. And then, TSA with multiple window functions is proposed to use TSA effectively even when the unexpected vibration modulation occurs.

3.1. Vibration Modulation Characteristics

For identification of the vibration modulation characteristics of the given planetary gearbox, this paper performed envelop analysis for the band-pass filtered signal around gear mesh frequency (GMF). Figure 4 represent identified vibration modulation characteristics of the planetary gearbox (normal condition) in 2kW testbed by investigating vibration level with regard to the ring gear's teeth. Vibration level was obtained by calculating RMS (Root Mean Square) value of the vibration signal for each gear tooth. Band-pass filter was designed to include only fundamental GMF as shown in Figure 4 (a). In addition, the range of the band-pass filter were
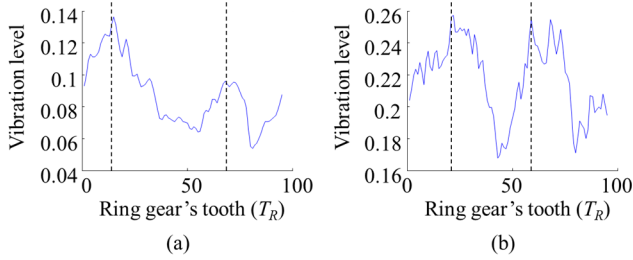
Figure 4. Vibration level of the planetary gearbox with regard to ring gear's tooth; (a) 1st gear mesh frequency is included for band-pass filter, and (b) 1st, 2nd, and 3rd gear mesh frequency is included for band-pass filter
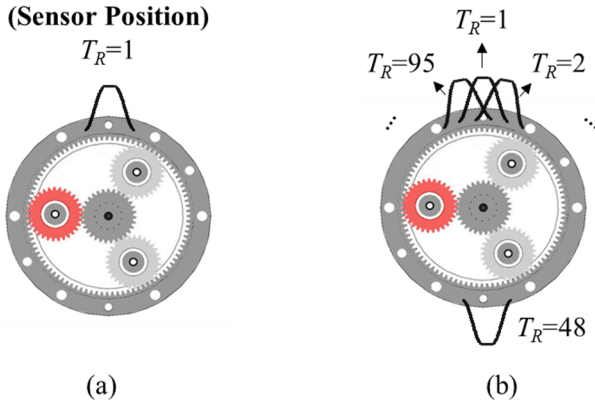

Figure 5. TSA with narrow-range window function; (a) Sole window function is employed (b) Multiple window functions are employed

further extended to 1st, 2nd, and 3rd GMFs to investigate more general characteristics of the gearbox as shown in Figure 4 (b). In Figure 4, x-axis represents ring gear's tooth which meshes with the planet gear of interest during one cycle of the carrier (i.e. during 95 teeth of the ring gear). If the assumption (the vibration is modulated by three planet gears passing the sensor during one carrier cycle) is assured, vibration level must have three local maximum values with the same intervals in the ring gear's tooth domain. However, there were only two local maximum values in Figure 4 (a) and (b) in this case, which are different from the assumption.

3.2. Multiple Window Functions

From Section 3.1, it was found that vibration modulation characteristics is not solely dependent to the revolution of the planet gears. In some cases, vibration level can be enlarged when the planet gears are located at particular tooth of the ring gear by several reasons. In these cases, the narrow-range window function centered on the sensor position may lose the opportunity to capture the abnormal signals generated by faulty tooth of the planet gear far from the sensor. Therefore, window function should be centered on the particular tooth of the ring gear where the vibration signal is amplified. Best solution to solve this challenge is to identify vibration
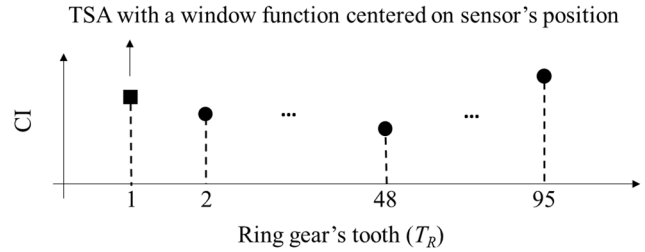

Figure 6. Condition indicators in the domain of ring gear's tooth

modulation characteristics to define optimal position of the narrow-range window function. However, it is difficult to define deterministic solution of vibration modulation characteristics because results of the envelop analysis are sensitive to detailed design of the band-pass filtering.

As an alternative way, this paper employed multiple number of narrow-range window functions located to every teeth of the ring gear. The comparison of the proposed approach with TSA employing a sole window function is illustrated in Figure 5. As shown in Figure 5 (a), the conventional TSA employs a sole window function centered on the sensor's position (T_R=1). Corresponding condition indicator (CI) is represented as a square marker in Figure 6 where T_R=1. However, this CI possibly fail to represent current health state of the gearbox where abnormal signal is generated far from the sensor due to the unexpected vibration modulation characteristics. Proposed method performs additional TSAs at each ring gear's tooth with the multiple window functions as shown in Figure 5 (b). Corresponding CIs are independently accumulated and monitored in ring gear's tooth domain as represented by circle markers in Figure 6. As a fault occurs in a planet gear, CI corresponding to one or more teeth of the ring gear will vary.

4. DEMONSTRATION

For the demonstration study, two kinds of artificial faults were manufactured to tooth number one of planet gears (T_P=1) as shown in Figure 7. First one is a tooth wear which was machined by peeling the surface of a gear tooth. Second one is a spall which was simulated by machining two thin lines
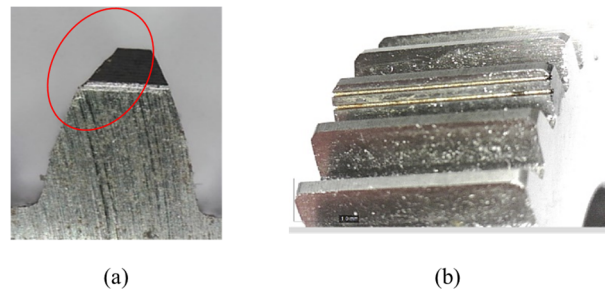

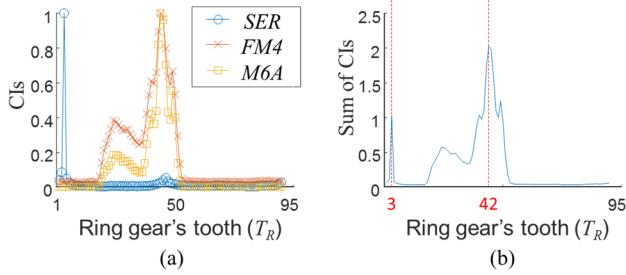Figure 7. Artificial fault of the gear; (a) a gear with tooth wear, (b) a gear with spall

Figure 8. Condition indicators (CIs) in ring gear's tooth domain where the gear with wear was used; (a) Condition indicators (b) Sum of the condition indicators

Figure 10. Condition indicators (CIs) in ring gear's tooth domain where the gear with spall was used; (a) Condition indicators (b) Sum of the condition indicators
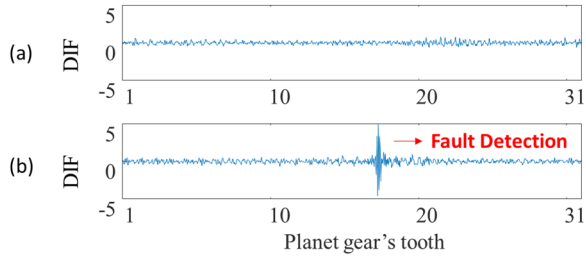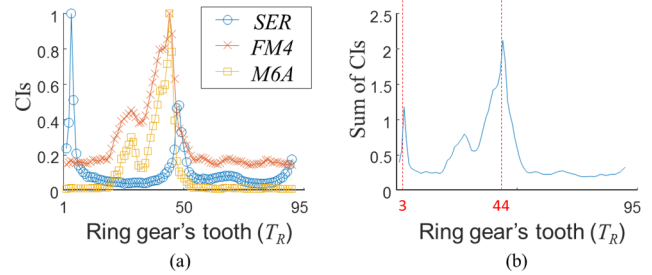

Figure 9. DIF in planet gear's tooth domain where the gear with wear was used; (a) Window function was centered on $T_R=3$ (b) Window function was centered on $T_R=42$
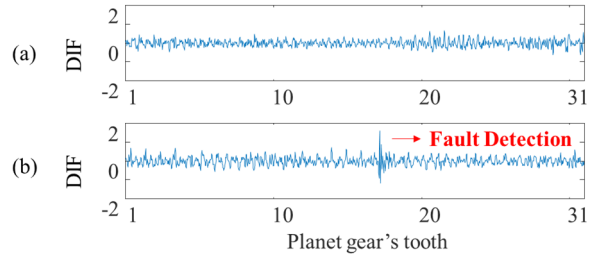

Figure 11. DIF in planet gear's tooth domain where the gear with spall was used; (a) Window function was centered on $T_R=3$ (b) Window function was centered on $T_R=44$

on the surface of a gear tooth. For comparison study, two gears were used so that a gear has only one type of fault. Two independent tests were ran for 60 seconds with the faulty gears (i.e. a gear with wear and a gear with spall). Rotational speed and torque were set to be 1500 rpm and 4Nm at the high-speed shaft. For TSA processing at each ring gear's tooth, this paper employed five-teeth Tukey window as a narrow-range window function, which was proposed by Samuel et al. (2004). From the test with the gear having a tooth wear, condition indicators (CIs) for every ring gear's tooth were obtained using the TSA with multiple window functions as presented in Figure 8. Figure 8 (a) compares three CIs (i.e. *SER, FM4* and *M6A*), and Figure 8 (b) shows sum of the three CIs in the ring gear's tooth domain to present general behavior of the CIs. In this study, trend of *SER* differed from the trend of *FM4* and *M6A*. *SER* had its maximum value near the sensor's position ($T_R=3$), whereas *FM4* and *M6A* had their maximum values around tooth number 42 of the ring gear ($T_R=42$).

Although faulty signature was visually found in the ring gear's tooth domain as shown in Figure 8, identification of the faulty signature in planet gear's tooth domain is valuable to understand physical meaning of increasing value of CIs. For example, Figure 9 (a) and (b) represent difference signals (*DIF*) in the planet gear's tooth domain which were obtained by locating Tukey window on tooth number 3 ($T_R=3$) and 42 ($T_R=42$) of the ring gear respectively. With the window function centered on near the sensor's position ($T_R=3$), TSA

couldn't detect the abnormal signals generated from the faulty tooth of the gear (Figure 9 (a)). Whereas, TSA with the window function centered on the tooth number 42 of the ring gear worked well in finding abnormal signals in planet gear's tooth domain. Interestingly, abnormal signal was found when tooth number 18 of the planet gear mesh with the tooth number 42 of the ring gear. In this moment, faulty tooth of the planet gear ($T_p=1$) simultaneously contacts with the sun gear. This is because of a fact that the abnormal planet gear was assembled to the gearbox so that the faults of the gear (left side of the gear surface in Figure 7) meshes with the sun gear. When the abnormal planet gear meshes with the ring gear, contact plane of the faulty tooth is positioned to opposite side of the faults of the gear (right side of the gear surface in Figure 7).

Figure 10 and Figure 11 represent condition indicators and difference signals which were obtained from the test using the gear with a spall. Processing procedures were set to be same as those employed for analyzing the previous case (a gear with wear). *FM4* and *M6A* in Figure 10 (a) represented similar trend with those in Figure 8 (a). In this case, they had their maximum values around tooth number 44 of the ring gear. On the other hand, *SER* had two local maximum values. First maximum value was found near the sensor's position which is same phenomenon as wear case in Figure 8 (a). Second maximum value was found around tooth number 50 of the ring gear. From this result, it can be said that *SER* partially represent similar trend to the *FM4* and *M6A*. Even

if the magnitude of abnormal signal was reduced, the results of Figure 10 and Figure 11 reached the same conclusions.

5. CONCLUSION

TSA with a narrow-range window functions have been effectively used for diagnostics of the planetary gearbox. However, it was found in this paper that such narrow-range window function is possibly unable to detect the abnormal signal when the window function is fixed on the sensor's position despite the unexpected vibration modulation characteristics of the gearbox. To solve this challenge, this paper proposed to employ multiple number of narrow-range window functions which are located to every teeth of the ring gear. The proposed method was demonstrated by the tests using a 2 kW testbed with two kinds of artificial fault of the planet gears. By the proposed approach, the abnormal signal generated far from the sensor was effectively detected.

Among three CIs employed in this study, *FM4* and *M6A* performed well compared to *SER*. Although FM4 and M6A successfully detect the fault of the gearbox in this case, they could fail to capture abnormal signal in different operating condition (e.g. varying rotational speed). For more general validation of the proposed fault diagnostics method, different kinds of condition indicators should be investigated to find best candidate in the future works. For even further study, causes of the unexpected vibration modulation characteristics should be identified. Simulation models of the planetary gearbox such as a finite element model or a lumped parameter model can be used for this purpose. In addition, a testbed that facilitates control of various operating conditions such as alignment condition and radial load condition will also be needed for the further demonstration of the proposed method.

Although the proposed method can advance the conventional TSA in the aspect of diagnostics accuracy, computational cost should be additionally considered. The proposed method performs multiple TSA processing as much as the number of ring gear's teeth, which means that computational cost significantly increases. In this case, conventional TSA required 1 second to process 60 seconds of vibration signal. On the other hand, TSA with 95 window functions necessitated 95 seconds of the processing time for the identical vibration signal. Because the processing time is longer than the running time of the gearbox, multiple TSA cannot be used as an on-line condition monitoring tool of the system. Computationally efficient signal processing technique, thus, is needed to be developed for the use of the multiple window functions as a real-time condition monitoring tool.

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