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A Novel Solution for the Coupled Faults Isolation in Gear Pairs Using the Conception of Frequency Tracking

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[1]***Abstract*—In engineering practice, there is always evidence for the existence of multiply faults in the gear meshing pairs. Different failures often occur simultaneously and thus increase the complexity of fault diagnosis. A literature review indicates that very limited work has been done to address the coupled faults isolation for gear pairs. To solve this issue, this work presents a novel approach to detect coupled faults of gear pairs using a conception of *Frequency Tracking*. The independent component analysis with reference (ICA-R) has been employed as the fault frequency tracking tool to extract critical frequency sources from multi-channel sensors. The frequency tracking scheme uses the prior knowledge of the gear rotational frequencies to construct suitable reference signals to incorporate into the ICA-R. Then the intrinsic frequency sources excited by every failure can be separated one by one. Hence, the coupled faults are simplified into single fault isolation problem. The experimental tests were carried out to evaluate the performance of the proposed approach. The test results show satisfactory isolation of coupled gear faults.**

***Index Terms*—Gear coupled faults, isolation, frequency tracking, independent component analysis.**

I. INTRODUCTION

Gear transmission systems have been widely used in rotational machines in various industrial applications. The malfunctions of the machinery caused by the failures of gear transmission account for 80 % [1] and the gear pair faults contribute a majority of the gear transmission damages [2]. Due to hash working environment, the gear pairs suffer from extreme wear and functional damages on their teeth [3]. Since any unexpected failures of the gear pairs could lead to significant economic losses, it is crucial to diagnose the incipient faults and prevent the gear transmission systems from malfunction [4].

Up to date, intensive study has been done and still undergoes in the fault diagnosis of gear transmission systems. As one of the most effective technologies, vibration analysis has been widely used in gear failure detection. Numerous vibration signal processing techniques emerge. These vibration analysis techniques include spectral analysis [5], time domain averaging [6], envelope detection [7], Wigner-Ville distributions [8] and wavelet transforms [9] etc. These methods have been proven powerful on processing vibration signals and are very useful for fault detection. However, their main limitations lie in their ability to isolate coupled faults. On the one hand, the above mentioned methodologies can only handle one direction measurement, i.e., vibration signal from one channel sensor only [2]. However, in practice the vibration of the gear meshing transmits towards various directions in the space according to the structural characteristics of the gear transmission body. As a result, much useful information in the other directions of the gear vibration has been lost if just one direction is analysed. On the other hand, these mentioned methodologies often need a noise eliminator in advance. Otherwise their performance may be subjected to progressive deterioration. Hence it is a big challenge for them in diagnosing multiply faults where occurrence of simultaneous faults presents. To overcome these two problems, the independent component analysis (ICA) has been introduced into the mechanical fault diagnosis. The advantage of the ICA is that it can find a suitable representation of multi-channel sensors [10].

Literature review [1], [10] indicates that the ICA is very useful for the gear fault detection, but limited work has been done to address the issue of coupled faults isolation. Li et al [1] discussed the pattern recognition problem of single and coupled faults in the gearbox using the ICA based method, but how to isolate the fault types in the coupled faults has not been mentioned. However, it is very important to know the fault types of the coupled faults in the gear pairs due to the requirements of arranging a suitable maintenance scheme. Considering that the diagnosis and isolation technology of single gear faults has already been well developed, we can decompose the couple faults into single ones and then the problem may become simple. Thus, the core issue to isolate the coupled faults in the gear pair is the transformation of couple faults into single ones. In our recent work [2] we found that the component analysis with reference (ICA-R) is useful for this kind of transformation. The ICA-R algorithm proposed by Lu and Rajapakse [11] is able to extract only one signal that satisfies a specific constraint (i.e. the reference) from multi-channel sensors. Taking use of this advantage of ICA-R, it is possible to extract the single fault information one

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by one from the vibration signals of the gear pair with couple faults. For instance, in a gear pair a crack occurs in the pinion while the gearwheel has a broken tooth. These form the coupled faults in the gear pair. To isolate them, we can use the ICA-R to extract the source component of the crack fault and then extract the source component of the broken tooth fault. Hence the problem of coupled faults diagnosis transforms into single fault diagnosis. As a result, it is possible to develop a novel solution for the isolation of gear coupled faults.

In the light of the recent studies on ICA-R, this paper presents a new approach for the coupled faults isolation for gear pairs. The new solution adopts the conception of *Frequency Tracking* that using the prior frequency knowledge of single faults to constrain the signal source separation of ICA-R. By doing so, the couple faults isolation issue can be transformed into single fault problem, which makes the couple faults isolation be simple and efficient. In comparison with the gear fault diagnosis reported in [1], [6], the proposed method in this work adopts frequency tracking based ICA-R to address the isolation of coupled faults in gear pairs. Thus, it further develops the gear multi-fault diagnosis solution and extends the application of ICA based mechanical fault diagnosis method.

Experiments have been conducted on a gear transmission test-bed to evaluate the performance of the proposed method. The analysis results validate the effectiveness of the newly proposed approach.

II. THE PROPOSED *FREQUENCY TRACKING* CONCEPTION

The measured vibration signals contain sufficient frequency information about the coupled faults of the gear pair. ICA-R is able to extract independent components that contain the fault frequencies. The ICA-R is an extension of ICA. Assuming the unknown independent components (ICs) matrix $\mathbf{s} = [s_1\ s_2\ \ldots\ s_n]^T$, a mixing matrix $\mathbf{A} \in R^{m\times n}$ is used to multiply $\mathbf{s}$ to obtain multi-channel sensor observations $\mathbf{x} = [x_1\ x_2\ \ldots\ x_m]^T$

$$\mathbf{x} = \mathbf{A}\cdot\mathbf{s}, \tag{1}$$

where m is the number of sensors. The ICA aims to find an inverse matrix $\mathbf{W}$ ($\mathbf{W} \in R^{n\times m}$) of A to recover the unknown ICs by $\hat{\mathbf{s}} = \mathbf{W}\cdot\mathbf{x} \approx \mathbf{s}$ [12]. The theories of how ICA calculates the inverse matrix $\mathbf{W}$ can refer to [1], [6], [12]. The ICA will separate all the ICs contained in $\mathbf{x}$. Hence, a discrimination process is needed to extract the ICs excited by the faulty gear pair. In order to only separate the desired IC but discard the unwanted ones, a reference is introduced into ICA and a correlation measure between the ICs and the reference is established [11]. This is the so called ICA-R. Simply, construct a suitable reference and then the ICA-R will output only one IC that has largest closeness to the reference [11]. The best reference has exact shape and amplitude of the IC of interest; however, it is unrealistic in practice. Since the vibration of gear meshing can be depicted by trigonometric functions [6], if the frequency information is known the reference could be designed using a trigonometric function with this frequency information, i.e. the *Frequency Tracking* (FT). We use a numerical simulation to illustrate how FT works.

Given that the unknown source matrix $\mathbf{s}$ is as

$$\mathbf{s} = \begin{bmatrix} s_1 = \cos(3t/2) + \cos(t/4) \\ s_2 = \cos(6t) + \sin(8t) \\ s_3 = \sin(t/6) + \sin(t/2) \\ s_4 = \sin(2t) + \cos(2t) \\ s_5 = \sin(t/2) + \cos(t) \end{bmatrix}, \tag{2}$$

a random matrix $\mathbf{A}$ is adopted to mix $\mathbf{s}$, and

$$\mathbf{A} = \begin{bmatrix} 0.757 & 0.706 & 0.823 & 0.438 & 0.489 \\ 0.743 & 0.0318 & 0.694 & 0.381 & 0.445 \\ 0.392 & 0.276 & 0.317 & 0.765 & 0.646 \\ 0.655 & 0.046 & 0.950 & 0.795 & 0.709 \\ 0.171 & 0.097 & 0.034 & 0.186 & 0.754 \end{bmatrix}. \tag{3}$$

Figure 1 shows the source signals $\mathbf{s}$ and Fig. 2 gives the mixed observations $\mathbf{x}$. It can be seen from the figures that the observations have been distorted severely from the sources. Fortunately, the ICA-R can recover the source of interest from the observations.

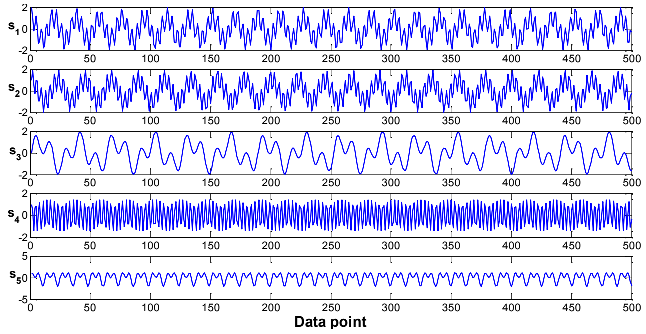


Fig. 1. The unknown source signals, $\mathbf{s}$.

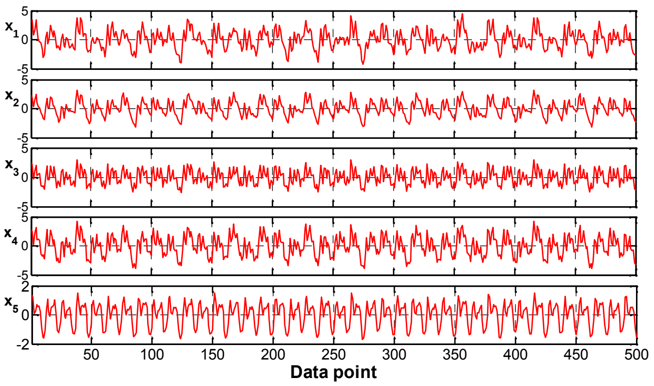


Fig. 2. The mixed observation signals, $\mathbf{x}$.

We construct a sine signal as the reference r to recover source s_4 from $\mathbf{x}$ and r is given as

$$r = \sin(2t). \tag{4}$$

It can be seen in (4) that the reference r contains the fundamental frequency 1/® . This means the reference r is used herein to track the frequency of the original source s_4. Figure 3 shows the ICA-R output result.

It is noticed from Fig. 3 that the FT based ICA-R has recovered the desired IC correctly. The extracted IC is similar to the source signal s_4. Similarly, we can extract source s_1, s_2,

s_3 or s_5 using the frequency tracking method.

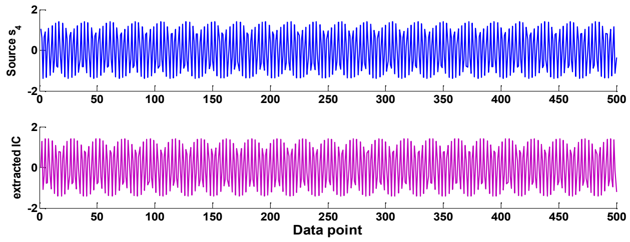


Fig. 3. The output IC of the ICA-R and the original source s_4.

As for the case of gear coupled faults isolation, the measured vibration signals may have two ICs: one is generated by the fault on the pinion and the other is excited by the gearwheel. Accordingly, we should construct two reference signals taking the prior frequency characteristics of the gear meshing movement into account in the ICA-R separation. By doing so we can get two desired ICs only related to the pinion fault and the gearwheel fault. Thus the problem of coupled faults diagnosis is transformed into single faults diagnosis.

III. EXPERIMENTS AND RESULTS

The experiments have been carried out in a gear transmission tester to evaluate the proposed fault isolation method. The experimental setup is shown in Fig. 4. It is a two-stage gear transmission and the two gear pairs are Z26/Z64 in the first shaft and Z40/Z85 in the second shaft. The coupled faults are seeded in the Z40/Z85 gear pair (see the arrow labels in Fig. 4). The Z40 gear has a cracked tooth and the Z85 tooth has a broken tooth.

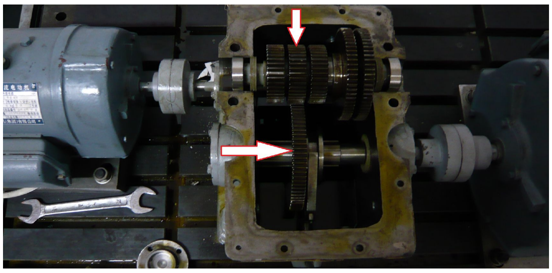


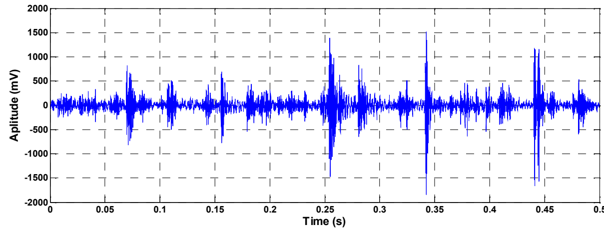
Fig. 4. The experimental setup, where the arrows label the faulty gear pair.

The vibration signals are recorded using two sensors located in horizontal and vertical directions under 1000 rpm of the driver motor. Table I lists the characteristic frequencies of the faulty gear pair.

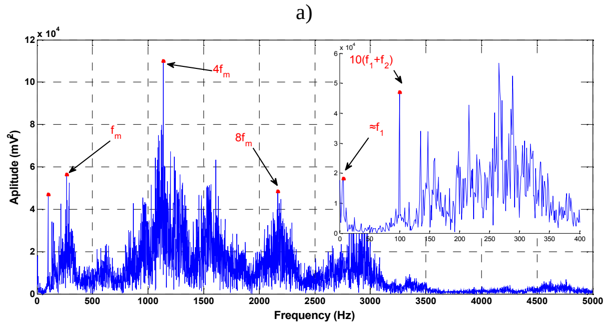
TABLE I. CHARACTERISTIC FREQUENCIES OF THE FUALTYGEAR PAIR.

Gear	Faulty frequency	Gear meshing frequency
Z40	f_1 = 6.77 Hz	f_m = 270.8 Hz
Z85	f_2 = 3.19 Hz	

It can be seen from Fig. 5 and Fig. 6 that although the measured vibration signals are contaminated by noise, there is evident existence of cycle impact generated by the meshing movement and/or the coupled faults excitations. The periodic time of the largest peaks in the time spectra in Fig. 5 and Fig. 6 is approximate 0.1 s, which is close to $1/(f_1 + f_2)$. In addition, large crests can be observed at $10(f_1 + f_2)$ in the frequency spectra in the figures. Hence, the spectra analysis demonstrates certain information about the occurrence of the coupled faults. However, it is difficult to isolate the faults according to the spectra. As mentioned before, we employed the ICA-R to deal with this problem.

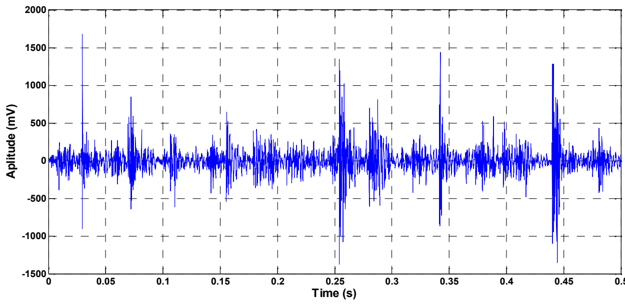


a)

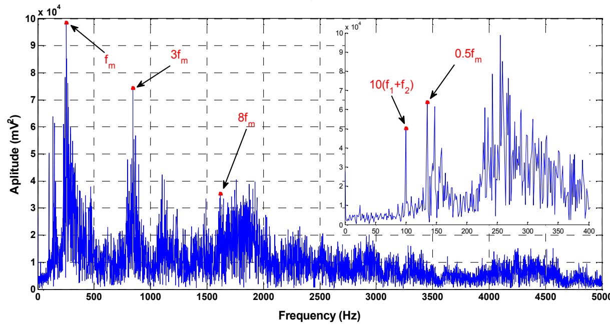


b)

Fig. 5. The time (a), and frequency (b), spectra of the horizontal sensor measurement.



a)



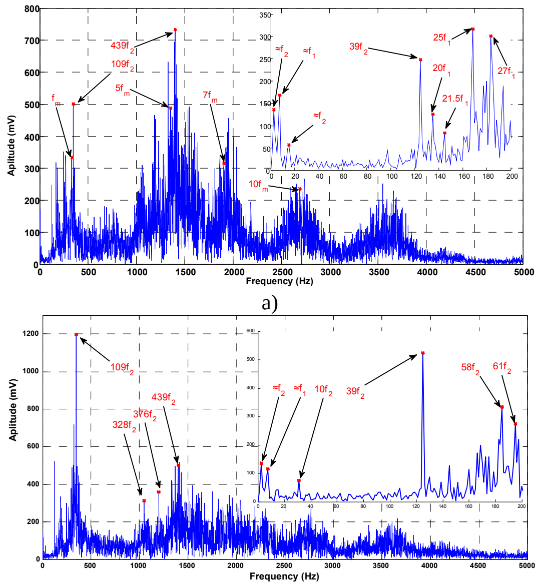
b)

Fig. 6. The time (a), and frequency (b), spectra of the vertical sensor measurement.

We construct the following two references to extract the ICs involved with the faults in Z40 and Z85, respectively.

$$\begin{cases} r_1 = \sum_{N=1}^{n} \sin(2\pi N f_1 t), \\ r_2 = \sum_{N=1}^{n} \sin(2\pi N f_2 t), \end{cases} \quad n = 1, 2, ..., \tag{5}$$

where n is the number of harmonics and n = 5 in this work. In (5), the faulty frequencies and their harmonics of the gear pair have been targeted. By tracking these characteristic frequencies, the ICA-R can extract the useful ICs to transform the coupled faults into two single fault signals by two steps. Figure 7 shows the ICA-R extraction results.



a)

b)

Fig. 7. The ICA-R extraction results: (a) cracked tooth fault extraction using r_1, and (b) broken tooth fault extraction using r_2.

It can be seen from Fig. 7(a) that by use of frequency tracking based ICA-R, sensitive frequencies about the pinion fault frequency f_1 is captured in the low frequency band. Most of the large crests in [0 Hz 200 Hz] are generated by the crack fault with the characteristic frequency f_1. In addition, there are frequency components related with the meshing frequency f_m and gearwheel faulty frequency f_2. Hence, the extracted source signal using the reference r_1 correctly presents the vibration behaviour excited by the crack fault in the pinion [1]. The same result can be observed in Fig. 7(b) when using the reference r_2 to recover the vibration source excited by the broken tooth fault in the gearwheel from the two sensor measurements. Abundant frequency information regarding to the characteristic frequency f_2 of the broken tooth has been captured by the proposed frequency tracking method. As a result, the coupled faults have been transformed into two single faults.

Since the coupled faults isolation has been transformed into single fault recognition problem, there are abundant well developed methods to deal with the single fault diagnosis issue. In this work we adopt the intelligent approach based on the short time Fourier transform (STFT) and Fuzzy neural network (FNN) classifier reported in [13] to isolate the separated two single faults, and the fault isolation precision is beyond 90.0 %. Thus, the proposed frequency tracking conception is able to deal with the isolation of coupled faults in gear pairs and satisfactory performance has been achieved. The proposed solution has been proven to be feasible and reliable for the isolation of coupled faults.

IV. CONCLUSIONS

Existing fault diagnosis and isolation methodologies are powerful in dealing with the gear single fault recognition issue. However, for the coupled faults isolation, very limited work has been done although the coupled faults in a gear pair occur frequently. In this work we have proposed a novel solution for the coupled faults isolation based on the Frequency Tracking. This newly proposed method adopts the independent component analysis with reference (ICA-R) to transform the couple faults into two single faults. The rotational frequencies of the gear pair were used to construct the reference signals for the ICA-R. By this frequency tracking, two independent sources involved with the single faults occurred in each gear of the gear pair can be extracted effectively. Then it can employ existing single fault diagnosis method for the fault isolation of the two extracted source signals. The experimental tests on the coupled faults isolation in a gear pair have been implemented and the analysis results show high efficacy of the proposed solution. Future work will extend this new method to other complex machines for the coupled faults isolation.

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