coatings

Editorial

Vibration-Based System Degradation Monitoring under Gear Wear Progression

Ke Feng [1], Qing Ni [2,*] and Jinde Zheng [3]

[1] School of Engineering, University of British Columbia, Kelowna, BC V1V 1V7, Canada; ke.feng@ubc.ca
[2] School of Mechanical and Mechatronic Engineering, University of Technology Sydney, Ultimo, NSW 2007, Australia
[3] School of Mechanical Engineering, Anhui University of Technology, Maanshan 243032, China; jdzheng@ahut.edu.cn
* Correspondence: qing.ni@outlook.com.au

check for updates

Citation: Feng, K.; Ni, Q.; Zheng, J. Vibration-Based System Degradation Monitoring under Gear Wear Progression. *Coatings* **2022**, *12*, 892. https://doi.org/10.3390/coatings12070892

Received: 9 June 2022
Accepted: 21 June 2022
Published: 23 June 2022

Surface wear is a common phenomenon in the service life of gear transmission systems [1]. Gear wear is the material loss from gear engaging surfaces due to sliding and rolling motions. In general, the propagation of gear wear would change the surface texture (at micro-level or macro-level), lubricating oil film thickness (if it has), and friction of the engaging gear pairs. The change in surface texture and friction can directly impact the gear contact load distribution and stress concentration. Consequently, the gear wear propagation can accelerate the occurrence of some functional failures and lead to the unexpected shutdown of the gear transmission system, which could cause enormous economic loss. Therefore, it is vital to monitor the gear wear progression so that reliable predictive maintenance-based decisions can be made to ensure a safe operation of the gear transmission system.

In general, the vibration signal measured from the gear transmission system can be affected by the surface wear progression [2]. The reason is that the gear mesh excitation and gear transmission ratio are sensitive to the gear surface geometry [3]. Therefore, vibration analysis can be a powerful tool for monitoring gear wear propagation. Also, compared with the wear particle analysis, vibration analysis has its unique advantages [4]. For example, the vibration characteristics can indicate the instant gear transmission performance change caused by gear wear. Thus, it can avoid the delay caused by the process progression of wear particle analysis. Therefore, vibration-based gear wear monitoring has attracted significantly increasing attention from researchers in recent decades. This editorial will give an overview of the development of vibration-based gear wear monitoring.

Some research works use the vibration features to monitor the system degradation behaviors caused by gear wear. For instance, as a prevalent health monitoring indicator, the gear meshing harmonic was applied to track the gear wear propagation in reference [5]. Also, the research [5] revealed that the higher-order gear meshing harmonics are closely relevant to the gear wear propagation progression. A similar conclusion was also drawn in [6]. In addition, the features of the cepstrum of vibrations were utilized for gear wear monitoring in [6], and the experimental results prove the effectiveness of the features from the spectrum and cepstrum in gear wear monitoring. However, the system degradation behaviors caused by gear wear propagation are highly complex. The dynamic interaction of multiple gear wear mechanisms and dynamic characteristics makes the wear propagation rate and patterns not constant. As a result, limited gear meshing harmonics do not have the capability of fully revealing the gear wear propagation status. Therefore, multiple gear meshing harmonics were included in [7] to track the gear wear propagation progression. In [7], the gear meshing harmonics were selected by a specific rule to derive two new gear wear monitoring indicators. With the help of the two developed gear wear monitoring indicators, the accumulated degradation behaviors and instant health status change induced by gear wear can be well indicated. Two endurance tests were arranged to demonstrate and validate the performance of the two gear wear monitoring indicators [7]. In addition to the gear meshing harmonic, some other techniques were also employed for gear wear monitoring. For example, the bispectrum of vibration signal was used in [8] to evaluate the gear wear progression. Based on the modulation signal bispectrum, the authors proposed a sideband estimator in [8], and its effectiveness was verified using the signals from a two-stage gearbox system.

In general, gear meshing harmonics and the bispectrum are closely relevant to the wear-induced gear tooth profile change. In the progression of gear wear, the micro-level surface morphology also changes significantly. To quantify the gear wear-induced micro surface morphology change, the cyclostaionary analysis was applied and proved to be a promising tool. The relationship between surface roughness and the second-order cyclostaionary (CS2) indicator was briefly investigated in [9,10]. However, due to the complex gear wear propagation process and the limitation of the experimental arrangement, insufficient conclusions were drawn in [9,10]. Later, the internal relationship of gear wear tribological features with the measured vibrations were proposed and proved in the study [11], as shown in Equation (1)

$$f_v \propto \nu_s \cdot f_s \tag{1}$$

where f_v (Hz) represents the frequency of the dominant sliding induced vibration signal, ν_s (m/s) denotes the sliding velocity of the engaging gear surface, and the dominant spatial frequency of the engaging surface morphology is written as f_s (1/m). In the research [11], the wear mechanism identification was first achieved using the online approach. More specifically, the abrasive wear and fatigue pitting were identified using the cyclostationary properties of the measured vibration signal, and the corresponding wear evolutions were accurately tracked. Inspired by the research [11], the capability of another cyclostationary analysis tool (cyclic-correntropy) in gear wear monitoring was evaluated in [12], and a novel gear wear monitoring indicator, namely the weighted cyclic correntropy operator, was proposed. Some endurance tests were conducted to demonstrate the performance of the developed gear wear monitoring indicator.

The above-discussed research works have contributed to the development of vibration-based gear wear monitoring and wear mechanism identification, significantly benefiting nondestructive gear wear monitoring and ensuring the safe operation of the gear transmission system. However, the characteristics of the vibration signal can only reflect the degradation trend of the gear transmission system, and the details of the contact status of the engaging gear can not be revealed. The knowledge of the gear contacting status is valuable for gear maintenance and gear design/optimization. The digital twin is an emerging technique for gear health management and has attracted significant attention from the research community and industry practices [13–15]. The digital twin model can help reflect the degradation status of the gear transmission system during wear progression, which can help the analyst understand the in-depth degradation mechanisms. Also, the remaining useful life (RUL) of the gear transmission system can be well predicted using the digital twin models. Therefore, the digital twin technique is of high practical value to gear wear monitoring and gear health management.

Based on the frame of the digital twin technique, the abrasive wear-induced tooth profile change was well predicted in [16]. In research [16], the root mean square (RMS) of the measured vibration signal was compared with the simulation signal to help update and calibrate the wear coefficient of the Archard wear model. Through the real-time communication between measurements of the physical structure and simulation models, the wear propagation rate change can be timely captured so that the abrasive wear-induced system degradation behaviors can be well indicated and the RUL of the gear system can be accurately predicted. Later, an improved Archard wear model was developed in [17], and this improved Archard wear model has been integrated into the digital twin frame for gear RUL prediction. Two run-to-failure tests with different lubrication conditions were used to verify the effectiveness of the developed vibration-based updating (digital twin) scheme for abrasive wear propagation prediction. The above two methodologies focus on the abrasive wear progression. However, in practice, multiple wear mechanisms interact with each other, resulting in highly complex system degradation progress [18,19]. Therefore, the technique which can handle multiple wear mechanisms is of great value for industrial practices. To this end, a novel fatigue pitting model was developed in [20] based on the Lundberg-Palmgren fatigue theory [21]. Then the dynamic model, developed fatigue pitting model, and Archard wear model were combined into twin models of the gear transmission system in [20]. To realize the real-time connection of twin models and the physical structure of the gear transmission system, a novel updating scheme, including RMS and second-order cyclostaionary indicator ICS2 [22], was also proposed to update the parameters of the twin models if necessary. The developed digital twin-based gear wear propagation prediction performance was illustrated and proved by two endurance tests [20].

Even though the above introduced digital twin-based gear wear methodologies have achieved satisfying prediction results, the prediction accuracy is highly enslaved to the fidelity of the digital twin models. Establishing a high-fidelity digital twin model is very costly, and high-level expert knowledge is required. Therefore, the intelligent digital twin model establishment technique/methodology is in vital need, which can help increase the practical value of the digital twin techniques for gear wear monitoring. Moreover, the digital twin technique will be a research hotspot in the area of wear analysis and gear health management.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ding, H.; Kahraman, A. Interactions between nonlinear spur gear dynamics and surface wear. *J. Sound Vib.* **2007**, *307*, 662–679. [CrossRef]
2. Randall, R.B. *Vibration-Based Condition Monitoring: Industrial, Automotive and Aerospace Applications*; John Wiley & Sons: Hoboken, NJ, USA, 2021.
3. Wojnarowski, J.; Onishchenko, V. Tooth wear effects on spur gear dynamics. *Mech. Mach. Theory* **2003**, *38*, 161–178. [CrossRef]
4. Ni, Q.; Ji, J.; Feng, K. Data-driven prognostic scheme for bearings based on a novel health indicator and gated recurrent unit network. *IEEE Trans. Ind. Inform.* **2022**, 1. [CrossRef]
5. Randall, R. A New Method of Modeling Gear Faults. *J. Mech. Des.* **1982**, *104*, 259–267. [CrossRef]
6. Žiaran, S.; Darula, R. Determination of the State of Wear of High Contact Ratio Gear Sets by Means of Spectrum and Cepstrum Analysis. *J. Vib. Acoust.* **2013**, *135*, 021008. [CrossRef]
7. Hu, C.; Smith, W.A.; Randall, R.B.; Peng, Z. Development of a gear vibration indicator and its application in gear wear monitoring. *Mech. Syst. Signal Process.* **2016**, *76–77*, 319–336. [CrossRef]
8. Zhang, R.; Gu, X.; Gu, F.; Wang, T.; Ball, A.D. Gear Wear Process Monitoring Using a Sideband Estimator Based on Modulation Signal Bispectrum. *Appl. Sci.* **2017**, *7*, 274. [CrossRef]
9. Yang, Y.; Smith, W.A.; Borghesani, P.; Peng, Z.; Randall, R.B. Detecting changes in gear surface roughness using vibration signals. In Proceedings of the Acoustics Conference, Hunter Valley, NSW, Australia, 15–18 November 2015; pp. 1–10.
10. Zhang, X.; Smith, W.A.; Borghesani, P.; Peng, Z.; Randall, R.B. *Use of Cyclostationarity to Detect Changes in Gear Surface Roughness Using Vibration Measurements, Asset Intelligence through Integration and Interoperability and Contemporary Vibration Engineering Technologies*; Springer: Cham, Switzerland, 2019; pp. 763–771.
11. Feng, K.; Smith, W.A.; Borghesani, P.; Randall, R.B.; Peng, Z. Use of cyclostationary properties of vibration signals to identify gear wear mechanisms and track wear evolution. *Mech. Syst. Signal Process.* **2021**, *150*, 107258. [CrossRef]
12. Feng, K.; Ji, J.; Li, Y.; Ni, Q.; Wu, H.; Zheng, J. A novel cyclic-correntropy based indicator for gear wear monitoring. *Tribol. Int.* **2022**, *171*, 107528. [CrossRef]
13. Tao, F.; Zhang, H.; Liu, A.; Nee, A.Y.C. Digital Twin in Industry: State-of-the-Art. *IEEE Trans. Ind. Inform.* **2019**, *15*, 2405–2415. [CrossRef]
14. Liu, M.; Fang, S.; Dong, H.; Xu, C. Review of digital twin about concepts, technologies, and industrial applications. *J. Manuf. Syst.* **2021**, *58*, 346–361. [CrossRef]
15. Errandonea, I.; Beltrán, S.; Arrizabalaga, S. Digital Twin for maintenance: A literature review. *Comput. Ind.* **2020**, *123*, 103316. [CrossRef]
16. Feng, K.; Borghesani, P.; Smith, W.A.; Randall, R.B.; Chin, Z.Y.; Ren, J.; Peng, Z. Vibration-based updating of wear prediction for spur gears. *Wear* **2019**, *426–427*, 1410–1415. [CrossRef]

17. Feng, K.; Smith, W.A.; Peng, Z. Use of an improved vibration-based updating methodology for gear wear prediction. *Eng. Fail. Anal.* **2021**, *120*, 105066. [CrossRef]
18. Weibring, M.; Gondecki, L.; Tenberge, P. Simulation of fatigue failure on tooth flanks in consideration of pitting initiation and growth. *Tribol. Int.* **2019**, *131*, 299–307. [CrossRef]
19. Morales-Espejel, G.; Rycerz, P.; Kadiric, A. Prediction of micropitting damage in gear teeth contacts considering the concurrent effects of surface fatigue and mild wear. *Wear* **2018**, *398–399*, 99–115. [CrossRef]
20. Feng, K.; Smith, W.A.; Randall, R.B.; Wu, H.; Peng, Z. Vibration-based monitoring and prediction of surface profile change and pitting density in a spur gear wear process. *Mech. Syst. Signal Process.* **2022**, *165*, 108319. [CrossRef]
21. Lundberg, G. Dynamic capacity of rolling bearings. *IVA Handl.* **1947**, *196*, 12. [CrossRef]
22. Raad, A.; Antoni, J.; Sidahmed, M. Indicators of cyclostationarity: Theory and application to gear fault monitoring. *Mech. Syst. Signal Process.* **2008**, *22*, 574–587. [CrossRef]