Using FBG Sensors for Tooth Fault Diagnosis in Spur Gears – an Experimental Comparative Study

Lior Bachar [1], Renata Klein [2], Jacob Bortman [1]

[1] *PHM Laboratory, Department of Mechanical Engineering, Ben-Gurion University of the Negev, P.O.B. 653, Beer-Sheva 8410501, Israel*
[2] *R.K. Diagnostics, P.O.B. 101, Gilon, D.N. Misgav 20103, Israel*

Abstract

Fault diagnosis of gear transmissions is commonly carried out by vibration analysis. Here we suggest a novel and comprehensive diagnostic methodology based on optic Fiber Bragg Grating (FBG) strain sensors. The use of FBG sensors for gear diagnostics is relatively new, despite their great potential in field systems. A designated test rig of spur gears was designed for this study. The expression of tooth face faults of different severities was noticed by the analysis of the synchronous average signal for various operational conditions, e.g., speed and load. A comparative study is performed, yielding similar diagnostic capabilities between strain and acceleration. The feasibility of using FBG sensors on gear transmissions, as well as the ability to monitor faults at different severities, suggest that FBG sensors can be utilized for gear diagnostics applications.

Keywords: gear diagnostics, FBG sensors, vibration signature, spur gears, condition monitoring, health indicator, tooth face faults.

Introduction

Gear transmissions are key elements in rotating machinery, e.g., helicopters, turbines, and vehicles. Gears usually work under harsh operating conditions, making them loud components with high tendency to fail [1-2]. Vibration analysis is a common and popular approach for health monitoring of rotating elements, e.g., gears, bearings, joints, shafts, etc. The vibrations are usually measured via piezoelectric accelerometers, despite their high sensitivity to electromagnetic interference and to the transfer function [1-2]. Fiber Bragg Gratings (FBG) are small, flexible, and electromagnetic-passive sensors, can be utilized for strain measurement. Since acceleration is the second derivative of displacement in time and strain is related to the displacement, both physical units reflect the vibrations of the machine.

Fault diagnosis of gear transmissions via FBG strain sensors has hardly been covered in literature [3-12]. A fundamental study to examine the strain signal under different operating conditions, e.g., speed and load, and for different health statuses of the gear has not been fully investigated yet. This paper presents a comprehensive experimental study to demonstrate the detection capability of local tooth faults in spur gears via the analysis of strain data measured with FBG strain sensors, compared to acceleration data, measured simultaneously.

Methodology

The diagnosis methodology is divided into the signal processing stage and the feature extraction stage (see Fig. 2). Here, the vibration signal refers to either acceleration or strain. The acceleration signal is simply obtained by multiplying the measured voltage by sensor's sensitivity. However, the data from the FBG consists of wavelengths λ_b, reflected after transmitting a light beam with a known wavelength of λ_0. The strain (ε) depends on the relative variation of wavelengths and a material scaling constant C_ε, as described in Eqn 1.

$$\varepsilon=(\lambda_b-\lambda_0)/(C_\varepsilon\lambda_0) \quad (1)$$

The vibration signal is synchronized with the rotational shaft's speed by angular resampling, followed by calculation of the synchronous average (SA) signal, i.e., a single averaged cycle of the shaft. SA is a common method used in gear diagnosis [1-2,13-16], utilizing the synchronous nature of gears for noise reduction and eliminating the contribution of other phenomena, not synchronized with the desired speed (e.g., bearings). Then, low order harmonics of the shaft's speed are filtered from the SA to eliminate their dominance in the SA. The difference signal is calculated, i.e., filtering gear mesh harmonics and their first pair of associated sidebands [14-16]. Finally, the envelope of the difference is calculated. This processing methodology has been proved as effective for local fault detection in gear transmissions [14-16].

The feature extraction methodology is based on the following four features: RMS & kurtosis (kurt) of the difference, and RMS & skewness (skew) of the envelope of the difference. When a local tooth fault occurs, it generates a sharp impulse response which is emphasized in the difference signal and its envelope [14-16] (see Fig. 1). Since the RMS reflects the energy of the signal, its value is expected rise in presence of such an anomaly. In addition, the sharp impulse in the difference signal is expected to arouse the kurtosis value, and the skewness of its envelope, which indicates the tendency of the signal to the positive/negative value.
The statistical z-score from the healthy baseline is calculated for each feature, resulting in a non-dimensional normalized value, counted in terms of the coefficient of the confidence interval σ (see Eqn 2) [15]. The equivalent distance of all scores is calculated and will be referred as a *health indicator*. The term "Health Indicator" (HI) refers to a numerical feature, constructed deliberately to evaluate the health condition of a system [17].

$$\text{z-score}=(x-\mu_h)/\sigma_h \quad (2)$$

where μ_h and σ_h are the mean and variance of the reference healthy baseline, respectively.

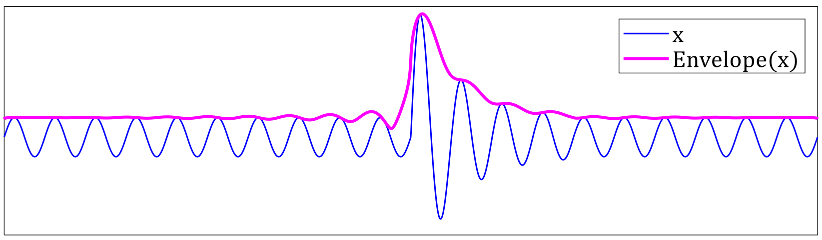

Fig. 1: A qualitative illustration of the difference signal and its envelope with an impulse response caused by the presence of a local tooth fault

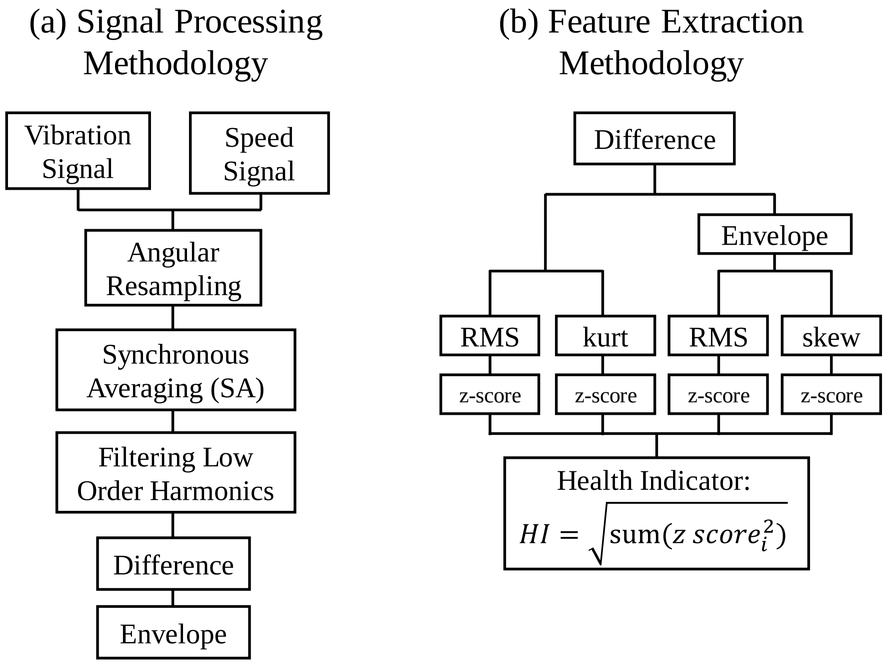

Fig. 2: (a) A scheme of the signal processing methodology. (b) A scheme of the feature extraction methodology.

Experimental Program

A designated test-rig of an open single-stage spur gear transmission was designed for the experiment (see Fig. 3-a). The driving input shaft is connected the pinion wheel (17 teeth), while the output shaft is connected to the gear wheel (38 teeth) from one side and subjected to torsional load provided by a hydraulic pump from the other side. Each shaft is supported by a couple of bearings, held with support brackets. Three types of sensors are mounted:

1) An optic FBG strain sensor, mounted along the bearing house. The sensor is connected to a Smart Fibers™ "SmartScan Aero Mini" interrogator, sampling data at 10[kS/s].
2) Dytran™ 3053B2 three-axial piezoelectric accelerometer, mounted on the support bracket. The sensor is connected to a National Instruments™ (NI) data acquisition system via PXI-4496 module, sampling data at 50[kS/s].
3) A Honeywell™ 3010AN magnetic pick-up tachometer, connected to both the interrogator and the NI units.

The examined faults in this experiment are local tooth face faults, expressed by a removal of material from part or the entire tooth width. Four severities of tooth face faults are seeded in the output gear wheel – A Partial Tooth Face Fault (PTFF) with material removed from 75% of the tooth width (see Fig. 3-b), and three levels of Full Tooth Face Fault (FTFF) with material removed from the entire tooth width at different sizes (see Fig. 3-c). The data is measured for two levels of rotational speed (15rps, 30rps) and two levels of load (5Nm, 10Nm). For both sensor types, six vibration signals of 60 seconds were measured for each combination of health status, speed, and load.

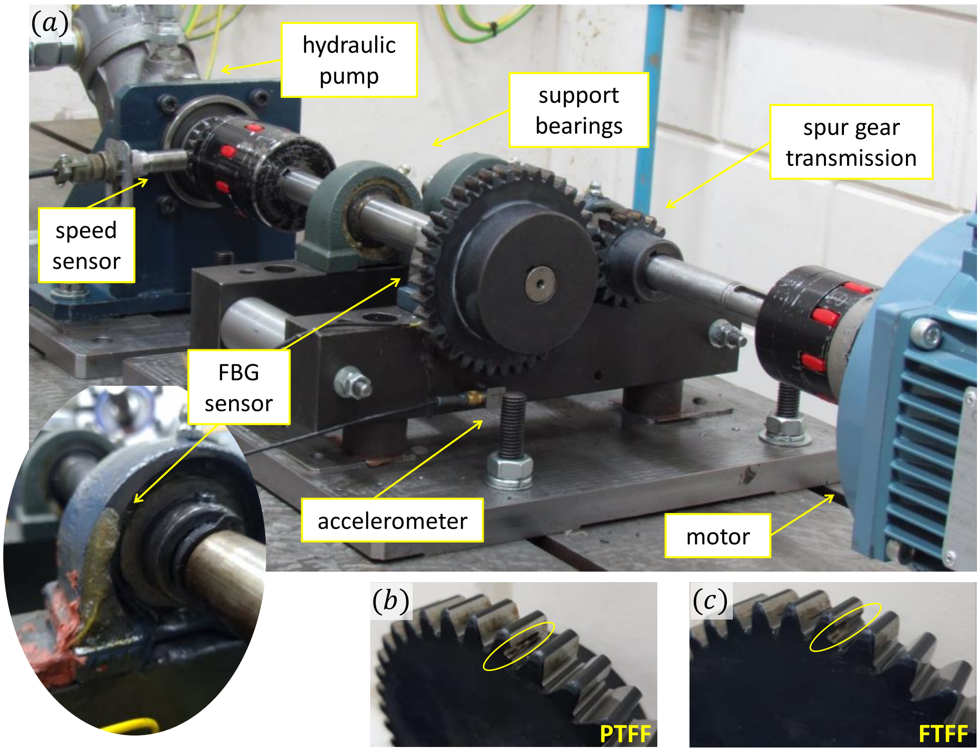

Fig. 3: (a) The spur gear test-rig. (b)-(c) pictures of the PTFF and FTFF, respectively.

Results

The difference signal is constructed from the filtered SA after eliminating the harmonics of the gear mesh frequency and their first pair of associated sidebands representing AM phenomena. Previous work shows that the expression of local tooth faults is emphasized in the far sidebands surrounding the gear mesh, associated with FM phenomena [15]. Fig. 4 compares the difference signal of the strain results for each health status, rank by fault's severity. We can notice the impulse response generated by the fault, emphasized along with health deterioration. The gradually increase in the magnitude of the impulse response generated by the full tooth face faults (FTFF) can be tracked, while the detection of the partial tooth face fault (PTFF) cannot be clearly achieved, as expected [15].

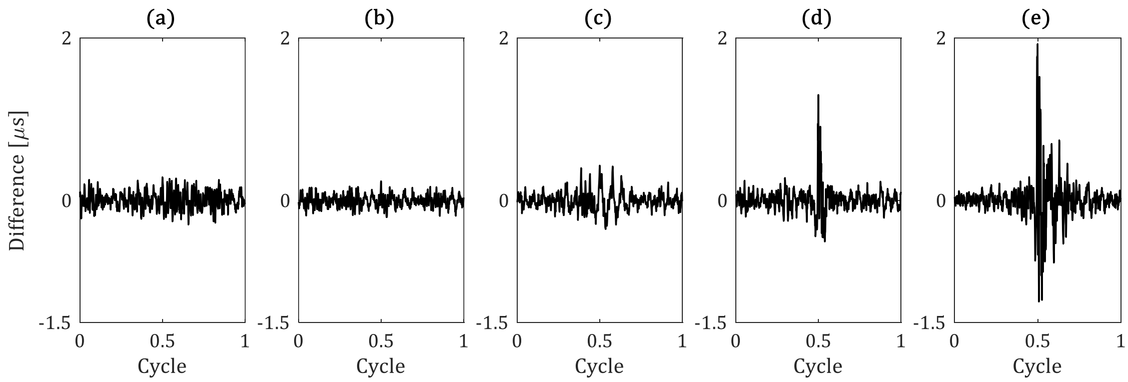

Fig. 4: Difference signal comparison (30rps, 10Nm): (a) Healthy ; (b) PTFF ; (c) FTFF1 ; (d) FTFF2 ; (e) FTFF3.

The results of the suggested health indicator (HI) are presented in Fig. 5 (in logarithmic scale), for each combination of speed (R) and load (L), comparing between strain (blue marker) and acceleration (magenta marker) results. For almost all cases, both the strain and acceleration results manage to separate the damaged statuses from the healthy status, and to rank the fault by severity. These diagnosis capabilities are clearer for measurement under the heavier loads, and strongly dependent on speed, as concluded in [15]. According to the analysis of the suggested HI, the acceleration results showed a slightly better performance than strain in terms of early detection (i.e., PTFF and FTFF1). The differences in the available bandwidth between acceleration (25[kHz]) and strain (5[kHz]) may explain this insight. The suggested HI is based on features that are expected to emphasize both sharp peaks and an increase in the energy of the difference signal and its envelope.

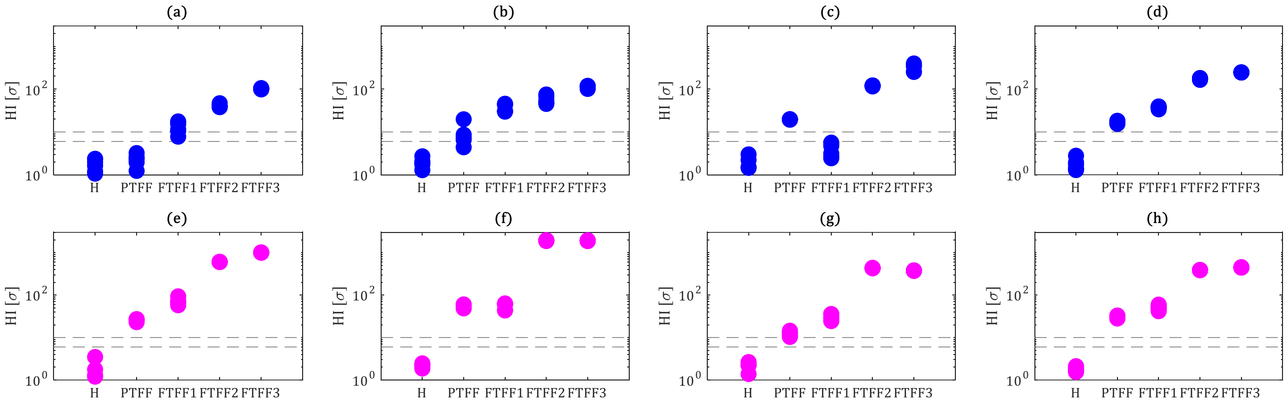

Fig. 5: HI comparison: Strain: (a) R15L5; (b) R15L10 ; (c) R30L5 ; (d) R30L10. Acceleration: (e) R15L5 ; (f) R15L10 ; (g) R30L5 ; (h) R30L10

Summary & Conclusions

This study examines the diagnostics capabilities of local tooth face faults in spur gears via optic FBG strain sensors. Experimental vibration data was collected for various combinations of speed, load, and health status from a designated test rig. The effects of the fault were studied by the analysis of the difference signal, constructed from the synchronous average (SA) after filtering low order harmonics of the shaft's speed. A comparison between strain and acceleration was performed by the analysis of a Health Indicator (HI), based on physical features extracted from the difference signal and its envelope. Both sensors managed to detect the fault, and in most cases to rank it by severity. The performance of the measured acceleration was slightly superior, probably due to bandwidth differences. The compact size and flexibility of the FBG sensors allow to mount them close to the transmission, unlike the conventional piezoelectric accelerometers. Thus, the foothold of FBG strain sensors in the field of health holds a great potential for diagnostics.

References

1. Kundu, P., Darpe, A. K., & Kulkarni, M. S. (2020). A review on diagnostic and prognostic approaches for gears. *Structural Health Monitoring*, 1475921720972926.

2. Kumar, A., Gandhi, C. P., Zhou, Y., Kumar, R., & Xiang, J. (2020). Latest developments in gear defect diagnosis and prognosis: A review. *Measurement*, *158*, 107735.

3. Baldwin, C. S., Kiddy, J. S., & Samuel, P. D. (2011, May). Towards development of a fiber optic-based transmission monitoring system. In *Photonic Applications for Aerospace, Transportation, and Harsh Environment II* (Vol. 8026, p. 80260N). International Society for Optics and Photonics.

4. Baldwin, C., Kiddy, J., Samuel, P., Coker, J., & Pines, D. (2007, September). Fiber optic sensors monitoring transmission ring gears. In *Photonics in the Transportation Industry: Auto to Aerospace* (Vol. 6758, p. 675808). International Society for Optics and Photonics.

5. Kiddy, J. S., Lewicki, D. G., LaBerge, K. E., Ehinger, R. T., & Fetty, J. (2011). Fiber optic strain sensor for planetary gear diagnostics.

6. Marcal, A. R. L., Zhang, X., Niu, H., & Di, F. (2019, December). FBG strain signal collection and its fault feature analysis for ring gear crack of planetary transmission in wind turbine. In *AOPC 2019: Optical Fiber Sensors and Communication* (Vol. 11340, p. 113401D). International Society for Optics and Photonics.

7. Zhang, X., Niu, H., Hou, C., Marcal, A., & Di, F. (2021). Tooth faults detection of planetary gearboxes based on tooth root strain signal of ring gear. *Measurement*, *170*, 108685.

8. Niu, H., Zhang, X., Marcal, A., Sun, W., & Wang, H. (2019, October). Fault Diagnosis of Planetary Gearboxes with Ring Gear Strain Signals Measured by Fiber Bragg Gratings. In *2019 IEEE SENSORS* (pp. 1-4). IEEE.

9. Qu, Y., Hong, L., Jiang, X., He, M., He, D., Tan, Y., & Zhou, Z. (2018). Experimental study of dynamic strain for gear tooth using fiber Bragg gratings and piezoelectric strain sensors. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *232*(21), 3992-4003.

10. Qu, Y., Zhang, H., Hong, L., Zhao, C., Tan, Y., & Zhou, Z. (2018, May). On research of incipient gear pitting fault detection using optic fiber sensors. In *2018 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)* (pp. 1-6). IEEE.

11. Shi, S., Qu, Y., Wang, J., Hong, L., Dhupia, J. S., & Zhou, Z. (2019, October). Feasibility Study of Online Monitoring Using the Fiber Bragg Grating Sensor for Geared System. In *2019 Prognostics and System Health Management Conference (PHM-Qingdao)* (pp. 1-6). IEEE.

12. Shi, S., Hong, L., Qu, Y., & Zhou, Z. (2020, October). A Novel Diagnostic Scheme for Gear Pitting Fault Using Fiber Bragg Grating Based Strain Sensors. In *2020 11th International Conference on Prognostics and System Health Management (PHM-2020 Jinan)* (pp. 385-390). IEEE.

13. Sharma, V., & Parey, A. (2016). A review of gear fault diagnosis using various condition indicators. *Procedia Engineering, 144*, 253-263.

14. Klein, R. (2012, September). Condition indicators for gears. In *Annual conference of prognostic and health management society* (pp. 1-8).

15. Bachar, L., Dadon, I., Klein, R., & Bortman, J. (2021). The effects of the operating conditions and tooth fault on gear vibration signature. *Mechanical Systems and Signal Processing, 154*, 107508.

16. Dadon, I., Koren, N., Klein, R., & Bortman, J. (2019). A step toward fault type and severity characterization in spur gears. Journal of Mechanical Design, 141(8).

17. Wang, D., Tsui, K. L., & Miao, Q. (2017). Prognostics and health management: A review of vibration based bearing and gear health indicators. *Ieee Access*, *6,* 665-676.