

Diagnosis of spiral bevel gear damage using the Wavelet transform model

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Abstract:

This study applies Wavelet analysis to develop a comprehensive method for detecting damage in spiral bevel gears within automotive drive systems. By utilising Wavelet analysis to examine the vibration signals of the gears, it is possible to identify spatial and temporal variations in the signals, thereby detecting signs of damage in the system. The integration of the Wavelet transform model allows for precise and comprehensive diagnosis of damage issues as well as predicting the vibrations of mechanical systems, particularly in complex meshing models. This not only enhances efficiency and accuracy in the study and handling of gear-related problems but also makes significant contributions to the field of mechanical engineering, especially in gear maintenance and damage diagnosis. Consequently, it improves the reliability and lifespan of automotive drive systems.

Keywords: Wavelet analysis; Spiral bevel gears; Damage detection, Vibration signals, Automotive drive systems.

1. Introduction

Bevel gears are essential components in many automotive and industrial machinery [1], [2]. With a circular design and sequential meshing teeth, bevel gears [3], [4] facilitate rotational motion between two intersecting shafts. The teeth are formed on a conical surface, causing their size and module to change along the length, tapering towards the cone apex. Specifically, straight bevel gears can transfer motion between two intersecting shafts at a fixed angle, most commonly 90 degrees, enabling efficient and precise direction changes. This provides flexibility in the design and operation, making straight bevel gears indispensable in various industrial and engineering applications. On the contrary, spiral bevel gears are notable for their ability to reduce vibration and noise compared to straight bevel gears of the same size. Due to their design, which minimises friction and impact

between teeth [5], [6], spiral bevel gears create smoother power transmission and less vibration, making them a popular choice in high-performance applications with low noise and vibration requirements. These applications include industrial machinery, automobiles, aircraft, and medical devices. Research in the development of damage analysis methods for both straight [7], [8] and spiral bevel gears plays a crucial role in enhancing the performance and reliability of drive systems [9], [10]. Methods include imaging techniques to observe and analyse tooth shape and size, simulation and modelling techniques to predict and assess damage, and kinematic analysis methods to measure and evaluate the performance of drive systems. The primary goal of these methods is to identify and evaluate common types such as wear, cracks, and mechanical deformation, thus providing suitable repair and maintenance measures to

extend the useful life and improve the performance of drive systems.

Wavelet analysis is a powerful tool for identifying structural damage, offering numerous advantages due to its high resolution capability [11], [12]. This method allows the decomposition of signals into frequency and time components, providing a detailed view of the signal variations across both variables. This separation of vibration components and noise facilitates easier damage detection, especially when there are sudden changes in the structure [13], [14]. The ability of wavelet analysis to detect abnormal or irregular variations in signals is highly useful for identifying damage, as these changes often indicate serious problems [15], [16]. Wavelet analysis can be tailored to meet specific application requirements, including selecting appropriate wavelet types, fine-tuning the analysis parameters, and choosing suitable resolution levels, thus enhancing the diagnostic and analytical capabilities of the method [17], [18]. Moreover, this method can be implemented on various hardware and software platforms, from personal computers to mobile devices, making it easily deployable in different real-world environments. Beyond vibration signal processing, wavelet analysis can be applied to a wide range of other signals, including images [19], [20], text [21], [22], and other numerical data, opening up many application opportunities in scientific and engineering fields. In summary, wavelet analysis is a powerful and flexible tool for identifying structural damage, with excellent resolution capabilities, the ability to detect sudden changes, flexibility, and ease of implementation. It has become an important tool for monitoring and diagnosing the condition of technical structures. Despite extensive research, there are still aspects that

need further exploration, such as the impact of environmental factors (temperature and humidity) on the performance and lifespan of bevel gears and the development of noncontact and non-destructive analysis methods to reduce inspection time and costs. These studies promise significant improvements in early detection and handling of gear damage, something that other methods cannot achieve.

2. Wavelet analysis model

In recent years, wavelet tools have become increasingly popular in signal processing due to their ability to analyse signals into time and scale components. This study will present the basic concepts and characteristics of wavelet, comparing it with traditional Fourier analysis that uses sine and cosine functions. Wavelet allows for the description of signals through shifted and scaled versions of the original wavelet function, providing higher accuracy for low frequencies over long periods and high frequencies over short periods. This flexibility makes Wavelet a powerful tool, opening up many applications in various fields. Wavelet analysis utilises the time-scale domain instead of the time-frequency domain, as Fourier does, and it is implemented through Wavelet transforms:

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)e^{-j\omega t} dt \quad (1)$$

Expression (1) is the sum of the signal $f(t)$ at all times multiplied by a complex exponential function. The result of the Fourier transform is the Fourier coefficients $F(\omega)$. These Fourier coefficients, when multiplied by a frequency sine wave of frequency ω , become the sine components that make up the original signal as shown in Figure 1. Geometrically, the process is as follows:

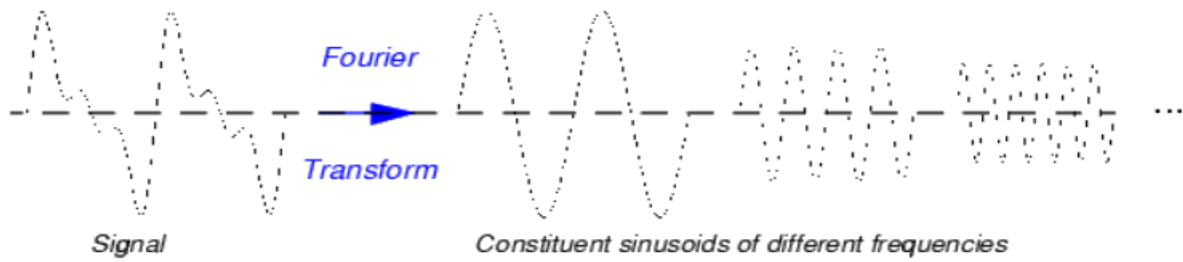


Figure 1. Signal analysis using the Fourier transform.

Similarly, the wavelet transform is defined as the sum over the entire time interval of the signal multiplied by the scaled and shifted versions of the wavelet function ψ .

$$C(\text{scale}, \text{position}) = \int_{-\infty}^{+\infty} f(t)\psi(\text{scale}, \text{position})dt \quad (2)$$

The result of the Continuous Wavelet transform (CWT) is a multitude of wavelet coefficients $C(\text{scale}, \text{position})$, which are functions of scale and position, as shown in Figure 2. Multiplying each coefficient by the wavelet at the corresponding scale and shift reconstructs the original signal.

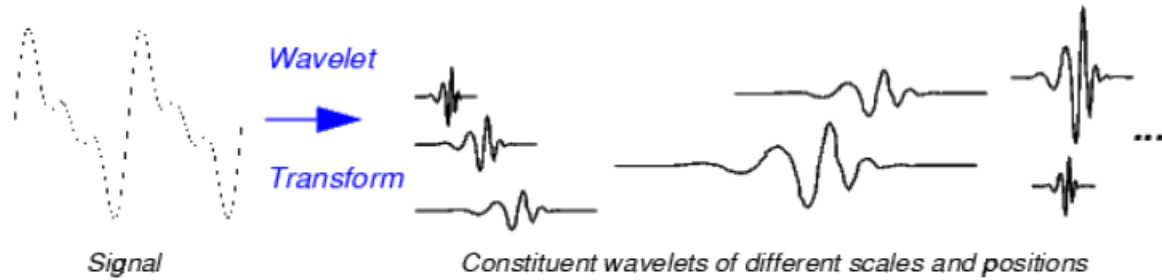


Figure 2. Signal analysis using Wavelet transform.

3. The Relationship between vibration frequency and damage in spiral bevel gears

Gear transmissions generate vibrations and oscillations at characteristic frequencies because of the precise meshing of gear teeth. These frequencies are related to rotational speed and the number of teeth, ensuring efficient power transmission, reducing noise and vibration, and increasing the durability and lifetime of the system. Analysing these frequencies provides crucial information about the operational condition of the gear transmission, enabling early detection of damage and timely maintenance:

$$F_c = Z_1 \cdot f_1 = Z_2 \cdot F_2 \quad (3)$$

Where: Z_1 and Z_2 are the number of teeth on the drive and driven gears, respectively; f_1 and f_2 are the rotational frequencies of the driving and

driven shafts. A normal gear transmission has frequency bands on each side, equally spaced by the rotational frequency f_1 of the input shaft and symmetrically around the meshing frequency F_c , as shown in Figure 3.

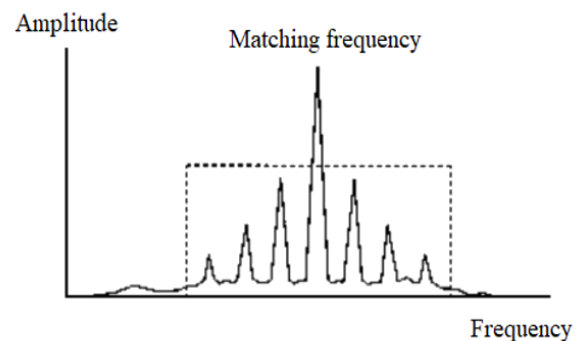


Figure 3. Frequency range and frequency spacing of the gear transmission.

The vibration signal of a gearbox is very complex, comprising oscillations of gears, rolling bearings, rotating shafts, and other

components. The structure of the vibration signal frequency spectrum includes frequency components from gear meshing, bearing frequencies, and shaft rotational frequencies, often in the form of harmonics. When a gear is damaged, the vibration signal changes,

reflecting deformations or deviations in the meshing process. Analysing these frequency components helps determine the operational condition of the gearbox and enables early detection of damage for timely maintenance.

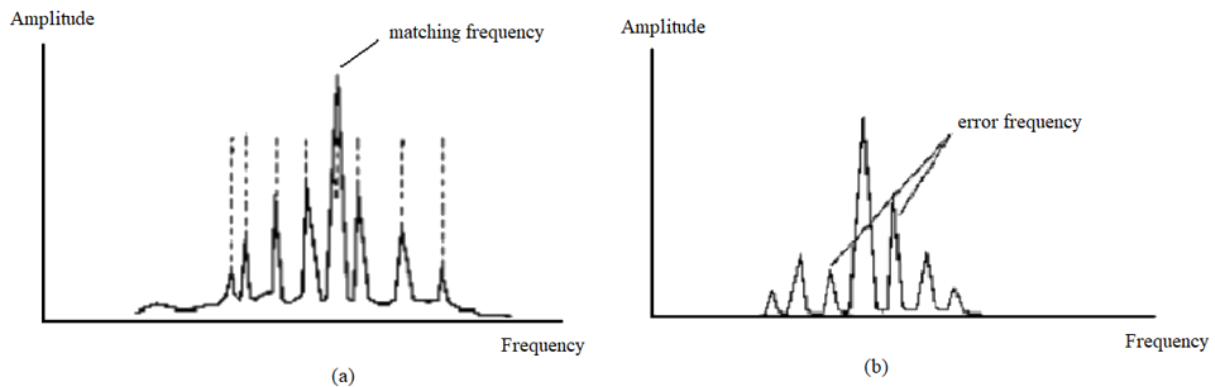


Figure 4. The vibration frequency shows gear damage.

(a) Axle distance is wrong; (b) Gear has cracks or broken teeth.

In the case of a broken or cracked gear, the frequency spectrum of a gear transmission with a broken tooth will have a higher amplitude on the right side of the meshing frequency, causing a characteristic asymmetry that indicates this type of damage and aids in diagnosing the problem as shown in Figure 4. On the contrary, if there is a misalignment in the gear shaft spacing, the vibration frequency spectrum will change. When gear teeth wear out, the variation in shaft spacing leads to changes in the spacing and amplitude of the frequency spectrum. When the shafts are too close together, the spacing between the sidebands moves toward the input shaft frequency, but the amplitude decreases significantly. These variations are key indicators for identifying issues related to shaft spacing and gear tooth wear, helping to achieve an effective diagnosis and maintenance of the transmission system.

4. Results and discussion

4.1. Vibration model of spiral bevel gears

The analysis of the vibration model using simulation is a crucial tool for evaluating and optimising the performance of gear mechanisms during meshing. Figure 5

illustrates the results of the vibration model analysis on a spiral bevel gear mechanism, using wavelet analysis to examine parameters such as deformation, stress, and displacement. This allows us to assess the overall deformation of the meshing position on the gear across various frequencies. The vibration results of Figure 8 demonstrate the overall deformation of the gears under the influence of different model frequencies, ranging from 9468.9 Hz to 29707.7 Hz. The deformation of the gears is measured and displayed using different colours, with maximum and minimum values identified for each vibration mode. Model analysis shows that the gear mechanism undergoes significant deformation at specific frequencies during operation, particularly in the upper part of the driving gear.

The deformation tends to concentrate on the upper part of the gear mechanism in most modes, indicating that this area is more susceptible to stress and vibration. At lower frequencies (9468.9 to 12600 Hz), as in Figure 6, higher deformation is observed, suggesting that the gear mechanism is more sensitive to vibrations within this frequency range. Therefore, these frequencies require special

attention during gear design and durability testing. Areas experiencing the highest stress and deformation are consistent in all vibration modes, highlighting critical points that may need reinforcement or design improvements to

enhance performance and durability. Reinforcing high-stress areas and optimising the design for low-frequency vibrations can provide significant benefits, improving the performance and durability of the gear system.

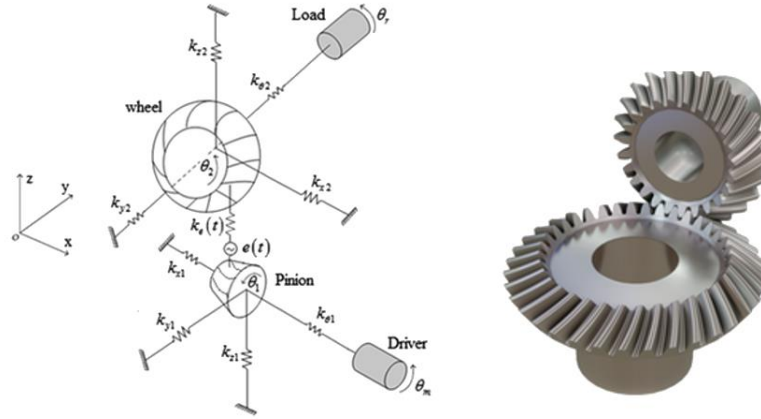


Figure 5. The dynamics of a spiral bevel gear model in mesh.

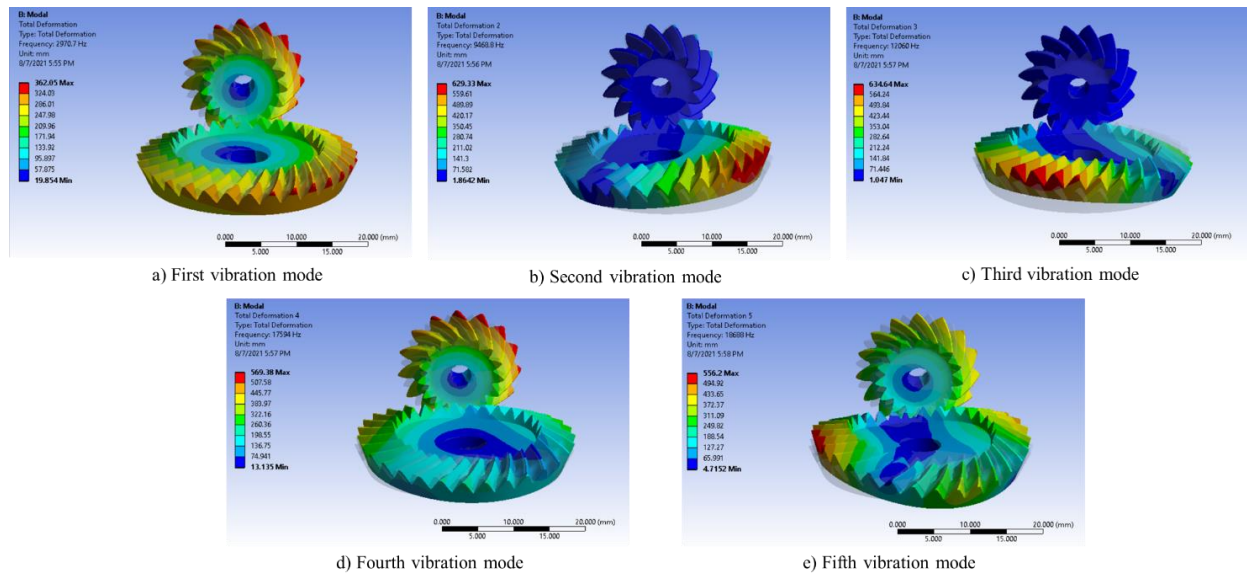


Figure 6. Gear vibration model through 5 modes.

The method studied in this paper offers significant advantages in the vibration analysis of spiral bevel gears during meshing. First, this method allows for the accurate modelling of the motion equations of the gear system, including dynamic variables, structure, and boundary conditions, resulting in a detailed and comprehensive mathematical model. Dynamic analysis through wavelet analysis helps identify characteristics such as frequency and amplitude of vibrations, enabling the recognition and analysis of specific vibration modes and their impact on system performance. In particular,

early detection of signs of damage such as deformation, stress, and displacement in gears facilitates timely maintenance and repairs, minimizing the risk of severe damage and extending the system's lifespan. This method also enables the assessment of the effects of different vibration frequencies, identifying sensitive frequencies that cause high deformation and stress, thus optimising the design and durability testing of gears. With the ability to simulate real-world scenarios and optimise design, this method not only improves performance and durability, but also reduces

maintenance costs and improves system operational efficiency. Due to these outstanding advantages, this method has become an essential tool for analysing and optimizing the meshing process of spiral bevel gears, contributing to the enhanced performance and reliability of mechanical drive systems.

4.2. Diagnosis of spiral bevel gear damage using the wavelet transform model

The combined wavelet analysis method is a powerful tool for diagnosing damage to spiral bevel gears, leveraging the strengths of both techniques. This method enables accurate modeling of motion equations for the gear system, including dynamic variables, structure, and boundary conditions, thus determining critical vibration parameters such as frequency and amplitude. Wavelet analysis decomposes the vibration signal into time and frequency components, which aids in the detection of local changes in the signal, which is particularly effective in identifying signs of damage such as cracks, wear, or deformation. When combined with dynamic and structural modelling, wavelet analysis provides detailed information on characteristic vibration frequencies and early signs of damage. This enables the identification and analysis of specific vibration frequencies, early detection of damage for timely maintenance, and improved accuracy in predicting the life expectancy and performance of the gear, while optimising the design to minimise damage risk. This model offers an effective and precise method of diagnosing spiral bevel gear damage, helping improve gear system design and maintenance, ensuring high durability and performance during operation.

The combined wavelet analysis method not only enhances diagnostic efficiency but also optimises maintenance measures, ensuring stable system operation and extending the lifespan of the gears. Its precision and ability to detect potential issues early make this method indispensable for managing and maintaining

mechanical drive systems. Based on Figure 7, the research group can draw scientific conclusions about the condition of spiral bevel gears when they are not damaged. First, the component signals indicate continuous amplitude variation without signs of abnormal deformation, suggesting stable gear operation. The Fourier transform shows the distribution of frequency components of the vibration signal, with amplitude peaks occurring regularly at characteristic frequencies. These frequency peaks do not exhibit sudden or abnormal amplitude increases, indicating that there is no damage or imbalance in the system. Finally, wavelet analysis displays the variation of the vibration signal over time and frequency. The frequency components are evenly distributed without sudden or abnormal changes in amplitude or frequency, indicating that the gear is operating normally. The results of the wavelet analysis confirm that the vibration signal has stable characteristics with no signs of damage, as illustrated in Figure 8. This combined method provides a powerful tool for monitoring and diagnosing the condition of gears, ensuring that any signs of damage can be detected early and addressed promptly, thereby maintaining the system's performance and durability. Based on Figure 9, the results of the wavelet analysis when gear damage corresponds to levels of 10%, 30%, and 100% allow us to draw scientific conclusions about the impact of damage on the gear system. In the case of 10% damage, the vibration signal shows an uneven variation in amplitude, reflecting a slight impact of the damage. The Fourier transform displays frequency peaks with higher amplitude compared to the undamaged case, indicating that the damage has begun to affect the system's vibration frequency. Wavelet analysis shows localized changes in amplitude and frequency over time, with an uneven distribution of frequency components. When damage increases to 30%, the vibration signal becomes more irregular, indicating greater instability. The Fourier transform shows

significantly increased amplitude peaks, especially at higher frequencies. Wavelet analysis reveals substantial variations in amplitude and frequency, with more uneven distribution of frequency components, reflecting greater instability due to the damage. In the case of complete damage (100%), the vibration signal shows an extremely uneven amplitude variation, reflecting a severe impact on the system. The Fourier transform displays very high amplitude peaks, particularly at lower frequencies, with the frequency range for this case illustrated in Figure 11. Wavelet analysis

indicates drastic changes in amplitude and frequency, with very uneven frequency components, reflecting severe instability due to complete damage.

In summary, wavelet analysis shows that the greater the level of damage, the more pronounced the variations in the vibration signal, with increasingly uneven amplitude and frequency changes and increased instability. This method allows for detailed detection and assessment of the impact of damage on the gear system, providing critical information for timely maintenance and repair measures.

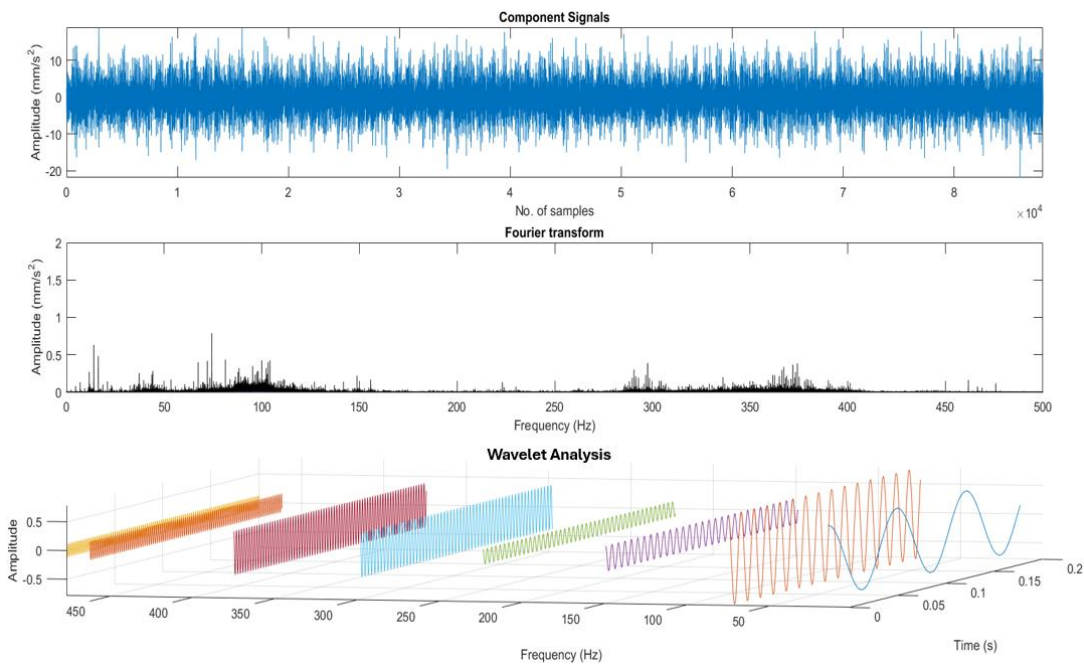


Figure 7. Wavelet analysis model of an undamaged gear.

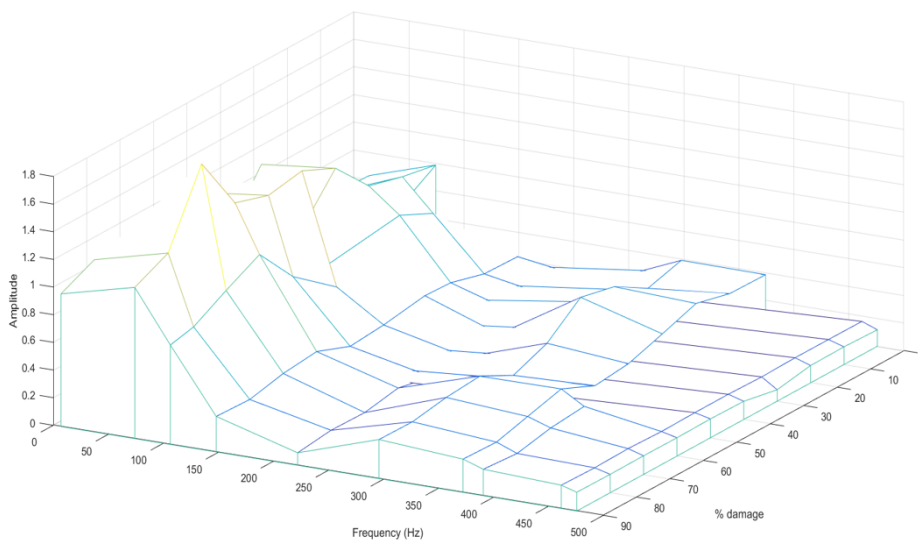


Figure 8. Frequency range of an undamaged spiral bevel gear model.

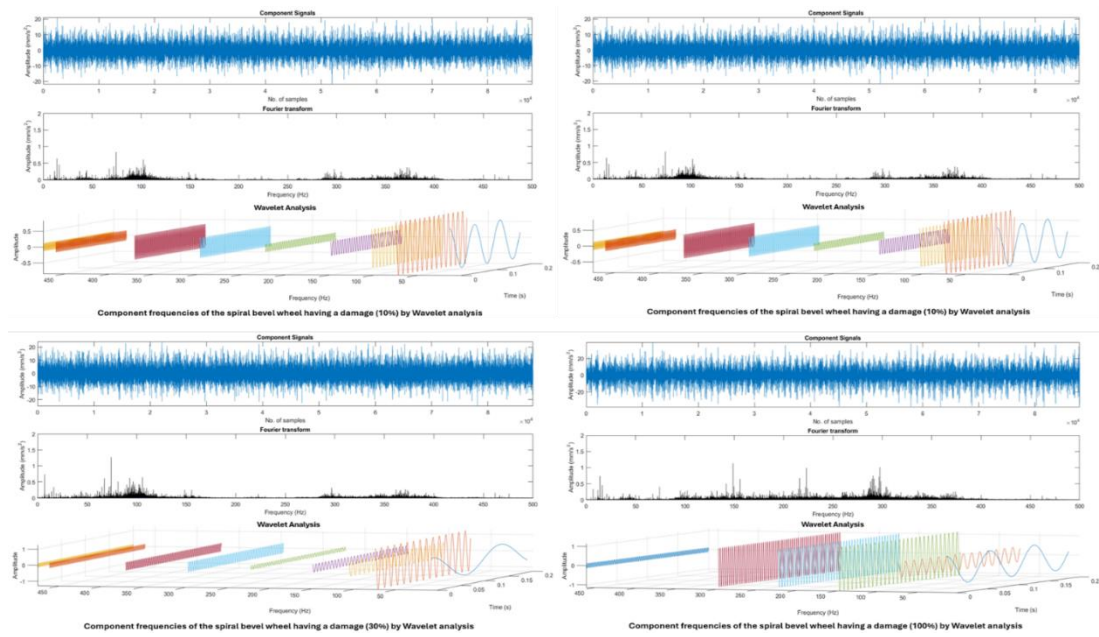


Figure 9. Wavelet analysis model of a gear with one defect (10-20-30-100%).

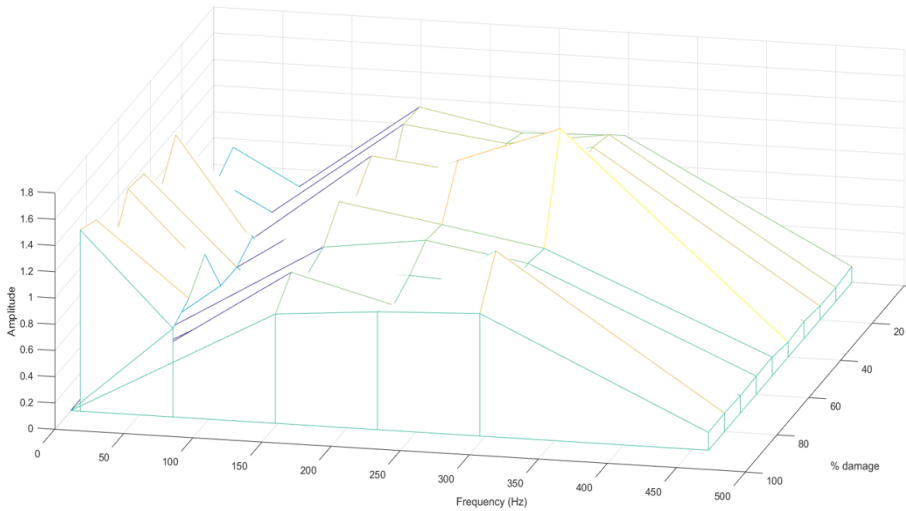


Figure 10. Frequency range of a spiral bevel gear model with one defect.

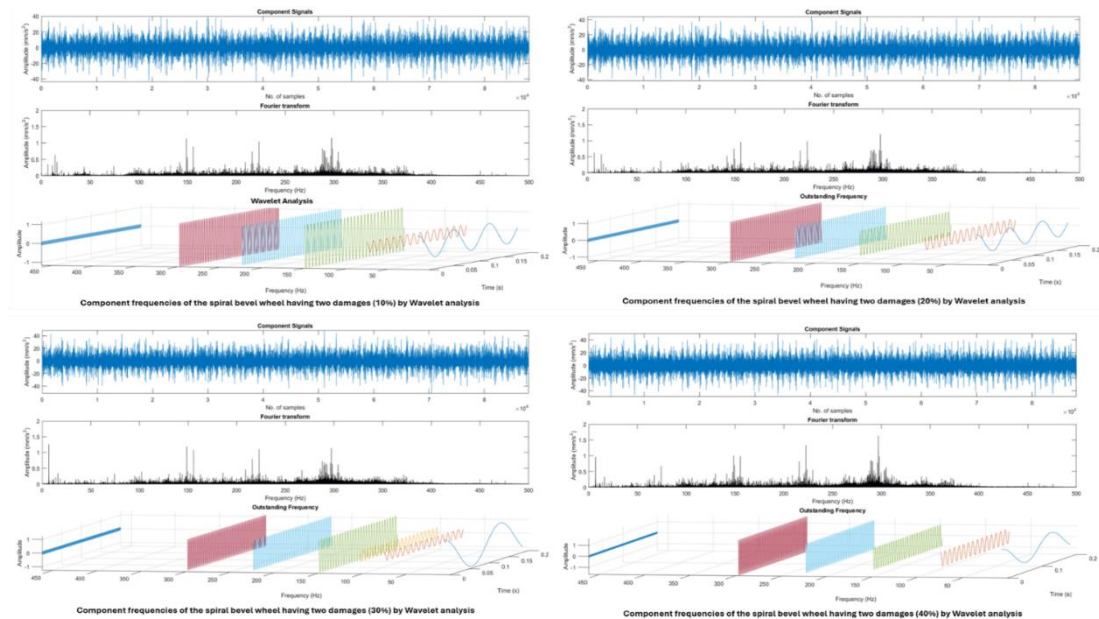


Figure 11. Wavelet analysis model of a gear with two failures (10-20-30-40%).

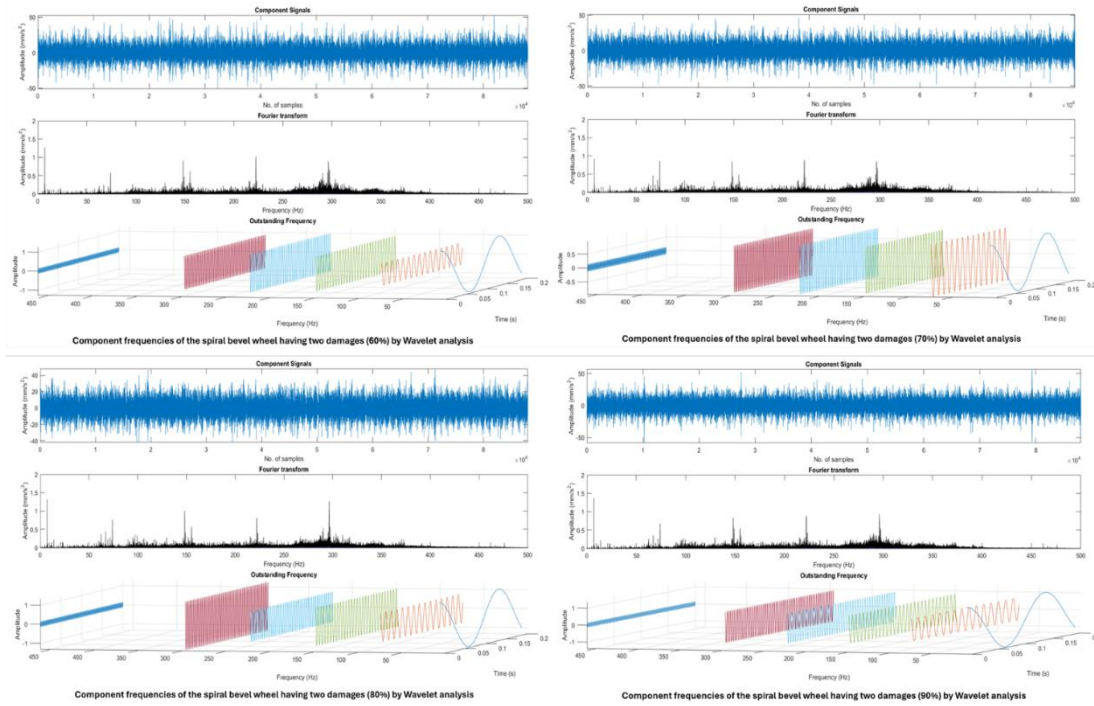


Figure 12. Wavelet analysis model when the gear has two failures (60-70-80-90%).

Based on Figures 11-12, the analysis of the wavelet model with two damages ranging from 10% to 90% reveals the impact of damage on the gear system. In the case of 60% damage, the vibration signal (component signals) shows uneven amplitude variation, with more noticeable disturbances compared to the undamaged case, reflecting increased instability. The Fourier transform displays frequency peaks with higher amplitude, particularly at higher frequencies, indicating that the two damage have significantly affected the system's vibration frequencies. Wavelet analysis indicates strong localized variations in amplitude and frequency over time, with uneven colour bands reflecting instability as a result of the damage. As damage increases to 70%, the vibration signal continues to show a more uneven amplitude, with disturbances in the signal becoming clearer, indicating a high level of instability. The Fourier transform shows significantly increased amplitude peaks at multiple frequencies, indicating that 70% damage has markedly altered the vibration frequencies and amplitude. Wavelet analysis shows very clear variations in amplitude and frequency, with unevenly distributed frequency

components reflecting strong instability. In the case of 80% damage, the vibration signal shows larger variations in amplitude, with increased disturbances, reflecting severe instability. The Fourier transform displays very high amplitude peaks at multiple frequencies, indicating that 80% damage has severely impacted the system's vibration frequencies and amplitude. Wavelet analysis shows very clear amplitude and frequency variations, with uneven frequency components, reflecting severe instability. In the case of 90% damage, the vibration signal shows extremely uneven amplitude variations, with significant disturbances, indicating severe instability. The Fourier transform shows extremely high amplitude peaks at multiple frequencies, indicating that 90% damage has critically impacted the system's vibration frequencies and amplitude. Wavelet analysis displays very pronounced amplitude and frequency variations, with unevenly distributed frequency components reflecting severe instability. Compared to cases with only one damage, models with two damages show much greater amplitude and frequency variations, as well as significantly increased instability. The

vibration signal shows more noticeable disturbances, and the Fourier transform displays frequency peaks with higher amplitudes. Wavelet analysis shows very clear amplitude and frequency variations, with colour bands indicating strong and uneven changes. This demonstrates that the presence of two damages significantly increases the risk of instability and severe damage compared to just one damage.

5. Conclusion

This study has demonstrated the effectiveness of combining wavelet analysis methods in diagnosing and evaluating damage in spiral bevel gears. Through the analysis of gear vibration and deformation signals under various conditions, from undamaged to severely damaged, the research has clarified the impact of different levels of damage on the durability and performance of gear systems. The analysis results indicate that damage increases local stress and vibration amplitude, especially when multiple damages occur simultaneously. Fourier transform and Wavelet analysis provide deep insights into the variation of frequency and amplitude over time, allowing for early detection of damage signs and the proposal of timely maintenance measures. Future research directions include applying the Wavelet method to various mechanical systems to verify and expand its applicability. Additionally, subsequent studies will focus on developing automatic analysis and diagnostic algorithms to enhance the accuracy and efficiency of damage detection. Integrating modern sensor technology for continuous and detailed vibration data collection is also a potential direction. Finally, expanding research on the effects of environmental factors such as temperature and humidity on the durability and performance of gears will provide a more comprehensive understanding of system operation under diverse real-world conditions.

These development directions not only improve the quality and reliability of gear systems but also contribute significantly to the sustainable development of the mechanical engineering industry.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests.

Ethical and informed consent for data usage

Data usage should not cause harm to individuals or communities. Clear and open communication regarding data collection, storage, and usage practices is essential to establishing trust and accountability.

Data availability and accessibility

Data is available within the article or its supplementary materials. The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Declaration of Interest statement

This is to certify that, to the best of the authors' knowledge; the content of this manuscript is original. The paper has not been submitted elsewhere nor has been published anywhere. The authors confirm that the intellectual content of this paper is the original product of our work, and all the assistance or funds from other sources have been acknowledged.

References

- [1] P. Choudhary, A. Niranjana, and P. Kumar, "Modeling and simulation of a bevel gear," in *In Advances in Mechanical Engineering and Technology*. Singapore: Springer Singapore, 2022, pp. 231-247.
- [2] W. -S. Kim et al., "Fatigue life simulation of tractor spiral bevel gear according to major agricultural operations," *Appl. Sci.*, vol. 10, no. 24, 2020, Art. no. 8898, doi: 10.3390/app10248898.
- [3] L. Tang, H. Tian, H. Huang, S. Shi, and Q. Ji, "A survey of mechanical fault diagnosis based on audio signal analysis," *Measurement*, vol. 220, Oct. 2023, Art. no. 113294, doi: 10.1016/j.measurement.2023.113294
- [4] X. Chen, Y. Zhang, Y. Su, Y. Zhou, and W. Gong, "A short time series rolling bearing fault diagnosis method based on FMTF-CNN," *Eng. Res. Express*, vol. 6, no. 2, 2024, Art. no. 025346, doi: 10.1088/2631-8695/ad4957.
- [5] A. S. Londhe, A. S. Ingale, and C. B. Khadse, "Bayesian regularization neural network-based fault detection system in HVDC transmission system," in *Smart Technologies for Energy, Environment and Sustainable Development*, vol. 1. Singapore: Springer Nature Singapore, 2022, pp. 601-607.
- [6] P. Boral, R. Gołębski, and R. Kralikova, "Technological aspects of manufacturing and control of gears," *Materials*, vol. 16, no. 23, 2023, Art. no. 7453, doi: 10.3390/ma16237453.
- [7] Y. Ma et al., "Design and study of a new QPQ combined with ultrasonic roller pressing method for gear surface strengthening," *Surface and Coatings Technology*, vol. 481, 2024, Art. no. 130619, doi: 10.1016/j.surfcoat.2024.130619.
- [8] A. S. Hammood et al., "Optimizing failure diagnosis in helical gear transmissions with stochastic gradient descent logistic regression using vibration signal analysis for timely detection," *Journal of Failure Analysis and Prevention*, vol. 24, no. 1, pp. 71-82, 2024, doi: 10.1007/s11668-023-01814-5.
- [9] Y. Yang, N. Hu, Y. Li, Z. Cheng, and G. Shen, "Dynamic modeling and analysis of planetary gear system for tooth fault diagnosis," *Mechanical Systems and Signal Processing*, vol. 207, 2024, Art. no. 110946, doi: 10.1016/j.ymssp.2023.110946.
- [10] X. Kang et al., "A novel ensemble convex hull-based classification model for bevel gearbox fault diagnosis," *Meas. Sci. Technol.*, vol. 34, no. 3, 2022, Art. no. 035017, doi: 10.1088/1361-6501/aca8c1.
- [11] O. D. Mohammed and M. Rantatalo, "Gear fault models and dynamics-based modelling for gear fault detection - A review," *Eng. Fail. Anal.*, vol. 117, 2020, Art. no. 104798, doi: 10.1016/j.engfailanal.2020.104798.
- [12] J. Wang, H. Wang, L. Guo, and D. Yang, "Modeling and fault identification of the gear tooth surface wear failure system," *International Journal of Nonlinear Sciences and Numerical Simulation*, vol. 22, no. 3-4, pp. 341-351, 2021, doi: 10.1515/ijns-2018-0221.
- [13] Y. Wang et al., "Mesh characteristic analysis of spiral bevel gear pairs considering assembly errors and tooth tip chipping faults," *Appl. Sci.*, vol. 14, no. 8, 2024, Art. no. 3227, doi: 10.3390/app14083227.
- [14] H. Wang, R. Yang, and J. Xiang, "Numerical simulation of gears for fault detection using artificial intelligence models," *Measurement*, vol. 203, 2022, Art. no. 111898, doi: 10.1016/j.measurement.2022.111898.
- [15] M. Nagode, B. Panić, J. Klemenc and S. Oman, "Fault detection and classification with the rebmix R package," *Computers & Industrial Engineering*, vol. 185, 2023, Art. no. 109628, doi: 10.1016/j.cie.2023.109628
- [16] T. Ouyang, X. Mo, Y. Lu, and J. Wang, "CFD-vibration coupled model for predicting cavitation in gear transmissions," *Int. J. Mech. Sci.*, vol. 225, 2022, Art. no. 107377, doi: 10.1016/j.ijmecsci.2022.107377.
- [17] Y. Su et al., "Small sample fault diagnosis method for wind turbine gearbox based on optimized generative adversarial networks," *Eng. Fail. Anal.*, vol. 140, 2022, Art. no. 106573, doi: 10.1016/j.engfailanal.2022.106573.
- [18] P. Goswami and R. N. Rai, "A systematic review on failure modes and proposed methodology to artificially seed faults for promoting PHM studies in laboratory environment for an industrial gearbox,"

- Eng. Fail. Anal.*, vol. 146, 2023, Art. no. 107076, doi: 10.1016/j.engfailanal.2023.107076.
- [19] P. Kundu, A. K. Darpe, and M. S. Kulkarni, "A review on diagnostic and prognostic approaches for gears," *Structural Health Monitoring*, vol. 20, no. 5, pp. 2853-2893, 2021, doi: 10.1177/1475921720972926.
- [20] Y. Chen and X. Mou, "Natural characteristics analysis and experimental test of spiral bevel gear pair in the tractor transmission system," *Advances in Mechanical Engineering*, vol. 13, no. 8, 2021, doi: 10.1177/16878140211037120.
- [21] T. Bettahar, C. Rahmoune, D. Benazzouz, and B. Merainani, "New method for gear fault diagnosis using empirical wavelet transform, Hilbert transform, and cosine similarity metric," *Advances in Mechanical Engineering*, vol. 12, no. 6, 2020, doi: 10.1177/1687814020927208.
- [22] S. Zhang et al., "State of the art on vibration signal processing towards data-driven gear fault diagnosis," *IET Collaborative Intelligent Manufacturing*, vol. 4, no. 4, pp. 249-266, 2022, doi: 10.1049/cim2.12064.