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REVIEW PAPER

Dynamics and Fault Diagnosis of Railway Vehicle Gearboxes: A Review

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Abstract: The railway vehicle gearbox is an important part of the railway vehicle traction transmission system which ensures the smooth running of railway vehicles. However, as the running speed of railway vehicles continues to increase, the railway vehicle gearbox is exposed to a more demanding operating environment. Under both internal and external excitations, the gearbox is prone to faults such as fatigue cracks, and broken teeth. It is crucial to detect these faults before they result in severe failures and accidents. Therefore, understanding the dynamics and fault diagnosis of railway vehicle gearbox is needed. At present, there is a lack of systematic review of railway vehicle gearbox dynamics and fault diagnosis. So, this paper systematically summarizes the research progress on railway vehicle gearbox dynamics and fault diagnosis. To this end, this paper first summarizes the latest research progress on the dynamics of railway vehicle gearboxes. The dynamics and vibration characteristics of the gearbox are summarized under internal and external excitations, as well as faulty conditions. Then, the state-of-the-art signal processing and artificial intelligence methods for fault diagnosis of railway vehicle gearboxes are reviewed. In the end, future research prospects are given.

Keywords: artificial intelligence; dynamics; fault diagnosis; railway vehicles gearbox; signal processing

I. INTRODUCTION

Rail transportation plays a crucial role in human daily life and economic development, and it has experienced rapid development in the past decades. Compared to other modes of transportation, rail transportation offers benefits such as large volume, low cost, and high safety. Furthermore, rail transportation is also more environmentally friendly. According to [1], rail freight transport emits 93% fewer carbon emissions per ton-kilometer compared to road freight transport. Since 2008, the Chinese government has constructed more than 37,900 km of high-speed railway lines, which are expected to double again by 2035 [2].

The safety and reliability of railway transportation are always the primary concerns for the rail transportation industry. The continuous increase in railway vehicle operation speed and carrying capacity raises the probability of failures in key traction transmission components. As an important part of the traction transmission system of railway vehicles, gearboxes are the key to the safe and smooth operation of railway vehicles. Railway vehicle gearboxes consist of driving gears, driven gears, gear shafts, gear shaft bearings, and gearbox housing, as depicted in Fig. 1. Straight gears and helical gears are two common types of gears used in railway transit equipment. Although the gearboxes for different types of trains are slightly different, they have common parts, as shown in Fig. 1. The gearbox is prone to failure due to the harsh working environment. A common type of fault is the occurrence of cracks in the housing, as shown in Fig. 2. Additionally, railway vehicle gearboxes may experience tooth cracks, tooth surface damage, oil leakage, and others [3,4]. In China, the Shaoshan series electric locomotive has experienced issues with gearbox oil leakage. The Dongfeng series locomotive has encountered significant wear, crack, broken teeth in the traction gear, pinion loosening, and gear cover deformation. Similarly, the HeXie series locomotive has also suffered from gearbox oil leakage, gear shaft fracture, and gear fracture [5]. The design life of the railway vehicle gearbox is typically the same as that of the entire vehicle.

Numerous studies have shown that condition monitoring and fault diagnosis technology can effectively prevent serious accidents. In fact, this technology has found extensive application in the critical systems of railway vehicles, including the bogie system, traction system, brake system, train electrical system, and information control system [7]. Existing review articles primarily focus on bearings and wheels [2,8–11]. While some review articles have covered railway vehicle gearboxes, they are relatively superficial [5,7]. Chen *et al.* [5] summarized the dynamics research progress on the gear transmission system of rail transits. Xie *et al.* [7] provides a brief summary of fault diagnosis in bogie gear with a smaller scope. Currently, there is a lack of comprehensive reviews specifically focusing on fault diagnosis in railway vehicle gearboxes, particularly in conjunction with dynamics research. As mentioned earlier, railway vehicle gearboxes are prone to frequent failures. Understanding gearbox dynamics is essential. To address this gap, this paper investigates the dynamics of the railway vehicle gearbox. Subsequently, this paper offers a comprehensive summary of the fault diagnosis methodologies for railway vehicle gearboxes.

The rest of this paper is organized as follows: in Section II, we summarize the latest research results on the dynamic characteristics of the gearbox under internal/external excitations and fault conditions. These studies' findings can serve as a guide for condition monitoring, structural improvement, and fault diagnosis of gearboxes. In Section III, the research status of fault diagnosis for railway vehicle gearboxes is summarized into two

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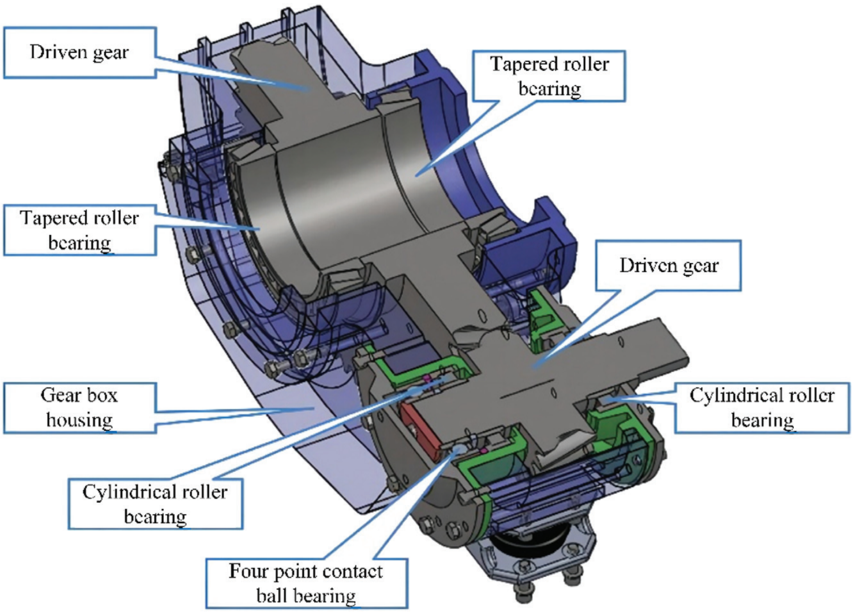

Fig. 1. High-speed train gearbox [6].

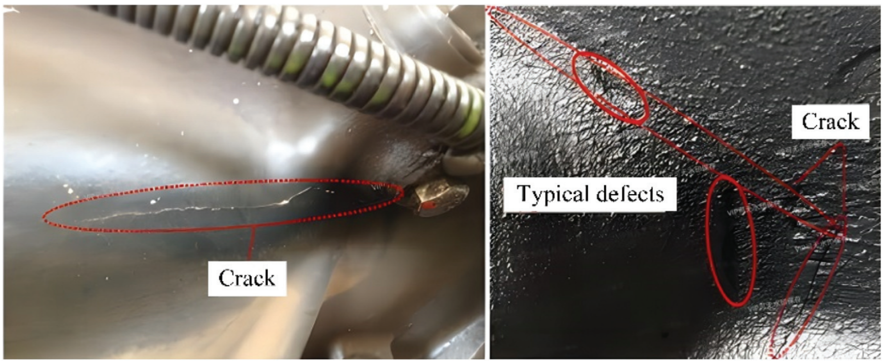

Fig. 2. Crack in gearbox housing [12].

categories: signal processing and artificial intelligence. Section IV discusses the future research prospects. Section V is the conclusion.

II. DYNAMICS OF THE GEARBOX UNDER INTERNAL/EXTERNAL EXCITATIONS AND FAULT CONDITIONS

The gearbox fault diagnosis is usually accomplished through the analysis of signals collected by sensors, including vibration, temperature, sound, and stress signals. However, observing the internal signals of the gearbox is challenging due to its closed-system nature. Therefore, external dynamic responses, such as vibration, are preferred, given their engineering feasibility. Fault diagnosis is achieved by analyzing and extracting the fault features in such external dynamic responses. Hence, understanding the dynamic characteristics of the gearbox is fundamental to the development of fault diagnosis methods, as fault characteristics are usually coupled with fault-irrelevant vibrations and complex operation condition effects. In this section, the gearbox dynamics-related research is reviewed in two categories: dynamics under internal and external excitation, and dynamics under fault conditions.

A. DYNAMICS UNDER EXTERNAL AND INTERNAL EXCITATION

When the railway vehicle is in operation, the excitation of the railway vehicle gearboxes can be categorized into two categories:

(1) Internal excitation. The internal excitation is generated within the system during the meshing process of the gear pair. Internal excitation mainly refers to the time-varying meshing stiffness of gears, gear errors resulting from incorrect manufacturing and installation, and time-varying bearing stiffness.

(2) External excitation. As a part of the railway vehicle, the gear transmission system is subjected to external excitations such as track irregularity, wheel–rail nonlinear contact, wheel polygonization, wheel flat, and traction motor harmonics.

1) DYNAMICS UNDER INTERNAL EXCITATION. Numerous studies have been conducted to investigate the influence of internal dynamic excitation on gearbox vibration. Huang *et al.* [13] developed a dynamics model of the traction system that considers the time-varying stiffness of meshing teeth pairs and the gear transmission errors. The results indicate that when the train operates at high speeds, the primary vibration frequencies of the gearbox are the meshing frequency and its harmonic frequencies. The internal dynamic excitation of the traction system can amplify both the vertical vibration of the frame and the gearbox. Hu *et al.* [14] used Adams multibody dynamic simulation software to establish a rigid–flexible coupling simulation model of the high-speed train gearbox transmission system. The study focused on the changing law of contact forces during the process of helical gear meshing and bearing rolling, as well as the motion stability of both large and small gears and bearing cages. The simulation results revealed that the vibration acceleration and displacement are higher for the pinion and pinion bearing compared to the gear and gear bearing, respectively. The gear and gear bearings exhibited greater stability. For quantitative analysis of the influence of internal excitation, Wei *et al.* [15] developed a multi-degree-of-freedom dynamics model. This model considers time-varying mesh stiffness, tooth gap, and bearing clearance. The results show that even a small backlash of the tooth surface will lead to a large vibration response in the traction gear system. The bearing clearance has a significant impact on the vibration displacement response of the system at low speeds, but its effect on the system becomes less significant at high speeds. The selection of appropriate bearing clearance and backlash of the tooth surface plays a crucial role in reducing the vibration of the gear transmission system of a small locomotive. Zhu *et al.* [16] established a dynamics model for high-speed train gear transmission considering time-varying meshing stiffness and time-varying meshing error. They also built a test rig for the traction gearbox. Various tests were conducted on the traction gearbox under various working conditions. The experimental results indicated that when the meshing frequency is equal to certain natural frequencies of the system, resonance occurs between the input and output shaft, with the vibration amplitude of the input shaft being greater than that of the output shaft. The frequency domain graph of the vibration acceleration exhibited peak values near the meshing frequency and its second harmonic. Additionally, peak values were observed near the rotation frequencies of the input and output shafts, as well as their harmonics. Ren *et al.* [17] developed a flexible gear meshing dynamics model and integrated it into the vehicle system dynamics model. Using this model, they investigated the impact of gear transmission on the dynamics of high-speed trains. The findings are that as the operating speed of the train increased, the gear meshing forces and oscillations in the transmission system intensified.

2) DYNAMICS UNDER EXTERNAL EXCITATION. Many researchers have investigated the vibration performance of wheelset-gearbox under external excitation, such as wheelset out-of-roundness, wheel polygon wear, track irregularity, or a combination of these excitations. Zhu *et al.* [18] analyzed data collected from a high-speed electric multiple-unit housing under service conditions and discovered that the modulation frequency of the axle rotation frequency and pillow-span impact frequency during train operation could worsen the vibration of the gearbox housing. Sun *et al.* [19] developed a rigid–flexible coupling dynamics model of railway vehicles using parameters from a specific type of Chinese High-Speed Rail (CRH) train. They incorporated a flexible transmission system dynamic model into this framework. The results indicate that gear mesh vibration in the transmission system has an impact on the vibration of the frame, gearbox, and motor. Gear meshing exacerbates the lateral vibration of the gearbox and motor, as well as the vertical vibration of the motor to some extent. Yang *et al.* [20] demonstrated that the acceleration vibration amplitude of the gearbox is lower when the train wheels are worn compared to new wheels. The reason may be that the material properties of the new wheel tread are unstable, and the worn wheel tread, after a period of operation, is more stable for high-speed train operation. Resonance fatigue can occur when the excitation frequency from the wheel–rail interaction is close to the natural frequencies of the structure. Liu *et al.* [21] conducted a 1:1 high-frequency excitation test using a rolling test rig within the speeds of 100–500 km/h. The results show that the wheel polygon wear is the primary excitation source of the wheelset system and determines the vibration level of the wheelset-gearbox system within speeds ranging from 100 to 400 km/h. Moreover, wear on the wheel polygon can induce resonance in the gearbox housing, resulting in torsional vibrations in the gear transmission system. To reveal the influence of the wheel polygonal fault on the gear transmission system under the traction condition, Zhao *et al.* [22] developed a Lagrangian form dynamics model of a railway vehicle with a gear transmission system. The results showed that the wheel polygonal faults have amplitude/frequency modulation effects on the time/frequency response of the gear system. The increase in the polygon order leads to severe aliasing effects and energy dispersion of the gear meshing frequency and its harmonics.

In addition to studying vibration characteristics, researchers have also investigated the dynamic stress field under external excitation. To analyze the dynamic response of the gearbox in the vehicle–track system, Wang *et al.* [23–25] developed a three-dimensional vehicle–track coupled dynamics model for high-speed trains, as shown in Figs. 3 and 4. This model is based on classical vehicle–track coupled dynamics and gear dynamics theory. The model considered nonlinear factors, such as nonlinear damping characteristics, time-varying mesh stiffness of the gears, and the wheel–rail contact relationship. They investigated the dynamic stress fields of the gearbox housing under wheel polygonal wear and wheel flat wear. The results show that the 20th-order polygonal wear can lead to the resonance in the gearbox housing and increase the maximum stress on the gearbox. Moreover, an increase in the length of the wheel flat leads to a further increase in the maximum stress value on the gearbox housing, especially when the length of the wheel flat exceeds 40 mm, resulting in a rapid escalation of the maximum stress value. In addition to simulation experiments, the authors also performed rig tests in the laboratory and field experiments on the Beijing–Shanghai high-speed rail line [26]. The results of the experimental studies align closely with the simulation, suggesting that polygonal wear can significantly influence the vibration of the gearbox housing. Under the 20th-order polygon wear, the gearbox housing will resonate, leading to severe vibration of the oil-level sight glass, increased stress, and a higher likelihood of cracking. Similarly, Zhu *et al.* [27]

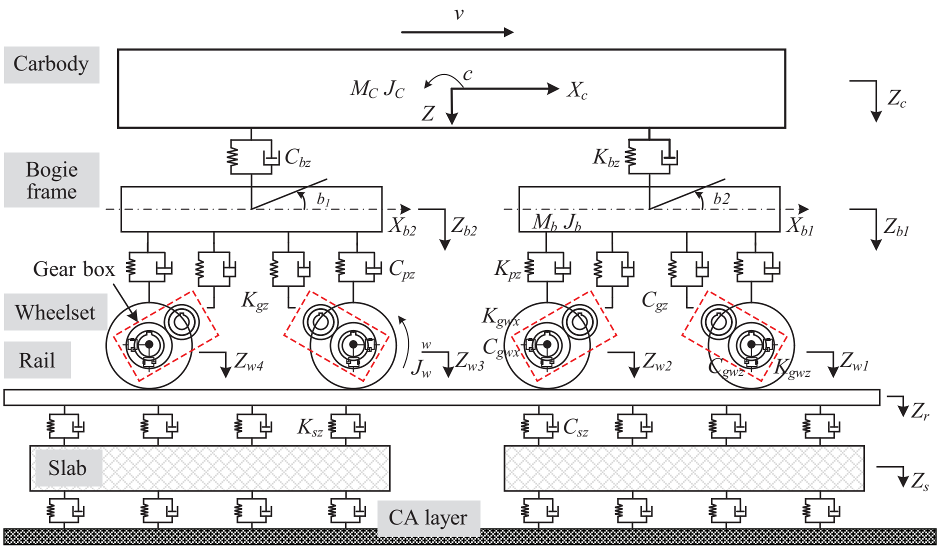

Fig. 3. Vehicle–track coupled dynamics model (elevation view) [23].

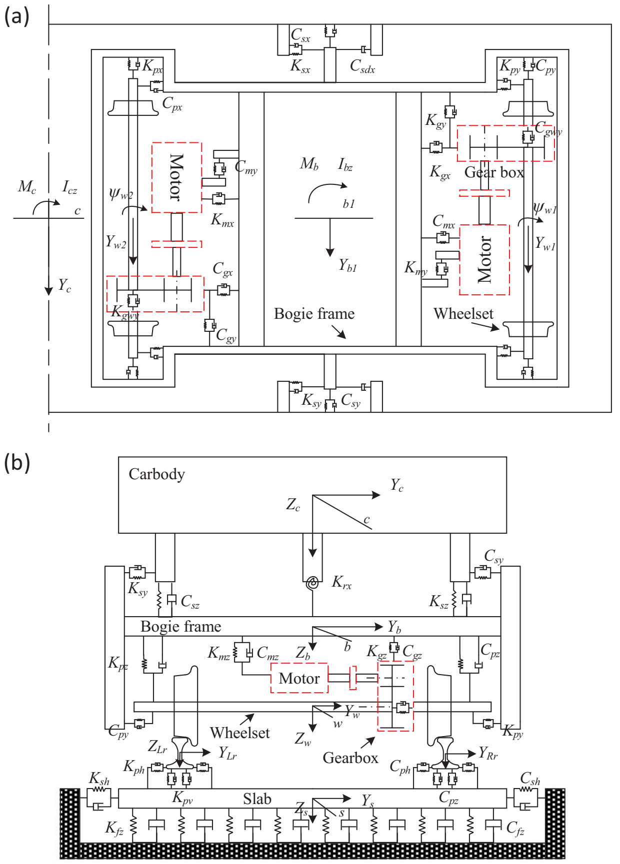

Fig. 4. Vehicle–track coupled dynamics model: (a) planform and (b) side view [23].

discovered not only the 20th-order polygonal wear of the wheel but also the 5th-order polygonal wear, leading to a significant increase in the local stress of the gearbox due to the wheelset roll motion. To investigate the impact of the torque on the vibration and stress of the gearbox housing, Hao *et al.* [28] established a multibody dynamics model that takes into account the elastic deformation of the wheelset and gearbox housing. Based on the electromechanical model, the vibration acceleration and dynamic stress of the gearbox housing are analyzed under three conditions: without torque, with ideal torque, and with harmonic torque. The results indicate that the traction torque amplifies the vibration acceleration and dynamic stress.

The results of the above studies show that wheel flat, wheel polygonal wear (especially the 20th-order polygonal wear of the wheel), and the harmonic torque of the traction torque can induce resonance in the gearbox. When resonance occurs, the stress near the oil window and the bottom section of the gearbox housing is relatively high. So, during the service process of railway vehicles, it is important to closely monitor the changes in the vibration environment of the vehicle to prevent gearbox resonance. Some studies [18,20,21,23,26,27] conducted rig tests or field experiments, thereby yielding more realistic results.

The existing dynamic models primarily consist of rigid–flexible coupling models. In ref. [19], the model considers the car body and wheelsets as rigid bodies, while the frame and gear pairs are considered as flexible bodies. The gearbox housing is considered as a flexible body in [26]. In ref. [27,28], the models both consider a flexible gearbox housing and wheelset. Additionally, studies [21–25] employed rigid-body assumptions, potentially diminishing the accuracy of the solution. The inclusion of flexible deformation in the gear pair and wheelset is preferable when constructing a realistic model and obtaining more precise calculation results.

3) DYNAMICS UNDER BOTH EXTERNAL AND INTERNAL EXCITATION. The railway vehicle gearbox generally operates under both internal and external excitations. Hence, considering internal and external excitations simultaneously is essential. To investigate the dynamic characteristics of high-speed train gearbox housing, Huang *et al.* [29] developed a multibody dynamics model that considers both internal and external excitations. In this model, internal excitations encompass time-varying stiffness, damping, and transmission error, whereas external excitation accounts for asynchronous motor harmonic torque and track irregularity. The results show that the dynamic characteristics of the gearbox under internal and external excitation can be revealed only by establishing the vehicle dynamics model.

The main frequency of the dynamic response of the gearbox reflects the harmonic torque frequency of the asynchronous motor and the gear meshing frequency. When the external excitation frequency is close to a certain order frequency of the gearbox, the stress amplitude of the gearbox housing will sharply increase. Huo *et al.* [30] conducted experiments to investigate the variation in contact load on the outer raceway's maximum loaded position of a gearbox bearing in a high-speed train. They also studied the characteristics and reasons for the variation in contact load at this position. It was observed that under specific operating conditions with small input torque and slow input speed, modal vibration occurs in the cage and shaft, leading to significant variations in the contact load. The variation coefficient of the contact load at the maximum load position was found to be linearly related to the root mean square of the acceleration measured at the bearing housing. In the study by Yang *et al.* [31], a rail vehicle model equipped with a helical gear system was developed to investigate the influence of wheel flats on the railway vehicle's gear system. When the wheels were in a healthy condition, the vibration acceleration of the gear system exhibited the meshing frequency of the gear system. However, in the presence of wheel flats, the frequency domain response showed the appearance of the gear system's meshing frequency and energy. If the vehicle speed exceeded 32 km/h, the sidebands and intense noise caused by the wheel flats gradually increased. As the vehicle speed continued to increase beyond 50 km/h, the noise generated by the wheel flats masked the gear meshing frequency. Wang *et al.* [32,33] developed a three-degree-of-freedom torsional vibration model for a spur gear transmission system of a typical locomotive. The model considers both internal and external excitations. Internal excitations include nonlinear backlash, static transmission error, and time-varying meshing. External excitations encompass motor torque variation and wheel–rail adhesion force fluctuation. Through this model, the authors found that the varying speed of the pinion will change the time-varying mesh stiffness, static transmission errors, and wheel–rail adhesion torque, which are called parametric excitation. Furthermore, this parametric excitation can reduce the performance of the gear transmission system, resulting in relatively large uncertainties in the dynamic response of the system. Zhou *et al.* [34,35] established a coupling model that considers the dynamic interactions between the electric drive subsystem and the mechanical subsystem. This model allows for the analysis of dynamic responses under various complex excitations, such as track irregularities, wheel flats, and time-varying gear mesh stiffness. The results show that the presence of wheel flats will exacerbate the wheel–rail impact and vibrations in locomotive components. Furthermore, the frequency spectrum of the traction motor current exhibits the gear mesh frequency and its harmonics. Wang *et al.* [36] established a novel vehicle dynamics model that incorporates gearbox housing, time-varying mesh stiffness, nonlinear gear tooth backlash, and track irregularities. The study revealed that wheel flats and wheel polygonal wear can cause high-frequency fluctuations in both the longitudinal creep force and gear mesh force, resulting in violent and complex torsional vibrations in the gear transmission system.

According to the above literature review, we can see the general principles for dynamic modeling and analysis: 1) by establishing a vehicle–rail coupling model that includes the transmission system, a more accurate dynamic response can be obtained; 2) considering both internal and external excitations in the model ensures a more realistic representation of the dynamic response; and 3) vehicle–rail coupled dynamics models can be utilized to assess the vibrational characteristics of the gearbox under various complex excitations, such as gear cracks, wheel defects, and gearbox housing cracks.

B. DYNAMICS UNDER FAULTY CONDITION

The aforementioned study provides insights into the dynamic behavior of gearboxes under various internal and external excitations. Understanding the dynamic characteristics of gearboxes in the presence of faults is particularly valuable for the development of gearbox fault diagnosis methodologies. To this end, the researchers conducted dynamics research under the condition of gearbox fault. These studies reveal the dynamic characteristics of gearboxes in a faulty state and provide a theoretical foundation for gearbox fault diagnosis. The types of faults in railway vehicle gearboxes include fatigue fractures (i.e., gear tooth crack and housing crack), gear spalling, gear wear, and misaligned cardan shaft.

1) GEAR TOOTH CRACK. Tooth crack is one of the most common faults in gearboxes, as shown in Fig. 5. Insufficient lubrication, excessive loads, or local material defects can lead to bending fatigue damage in gear teeth, resulting in tooth cracks. The presence of tooth cracks in railway vehicle gearboxes can lead to complete failure of the gear transmission system. Detecting tooth cracks early on can help prevent such failures. Wang *et al.* [37] studied the parametric resonance and stability of a cracked gear system for a railway locomotive. Time-varying meshing stiffness caused by tooth root cracks and the nonlinearity of the cracked gear system leads to the bending of the frequency response curve, multiple value phenomenon, and the nonlinear jump in the amplitude. The presence of a crack in the tooth root diminishes the damping effect on the resonance amplitude, leading to an increase in vibration amplitude and unstable operation of the railway locomotive.

For the smooth operation of railway vehicles, it is critical to understand the fault characteristics of the gear transmission under tooth cracking fault and to find the early tooth cracking fault in time. In theory, the localized faults of the concentrated defects, such as broken teeth, tooth surface spalling, and cracks, can generate periodic shock pulses. These faults can also generate amplitude modulation and frequency modulation. Liu *et al.* [38] established a

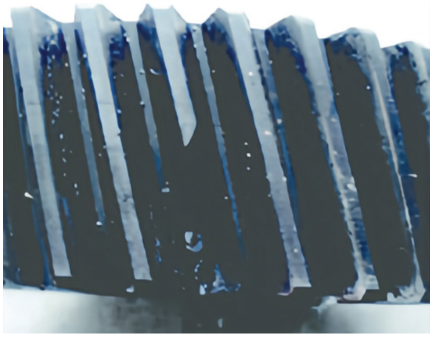

Fig. 5. Subway gearbox bevel gear tooth crack [44].

kinematic model of a high-speed train transmission system, and the fault characteristics of bearing, wheel, and gear elements are studied. When a tooth root crack occurs in a gear, the time–domain response of the driven gear nodes exhibits a clear period, which corresponds to the rotating period of the gear with the crack. In the spectrum of the time–domain response, new frequency components appear around the natural frequencies and meshing frequencies. The gear fault frequency primarily manifests in the gear meshing frequency band. Liu *et al.* [39] obtained the vertical vibration acceleration of the locomotive body, bogie frame, wheelset, and motor under different degrees of tooth cracking using a dynamic locomotive model with gear transmission. The results indicate that when a tooth root crack occurs in the pinion of the gear transmission system, the vibration signal exhibits the pinion's rotational frequency and its harmonics. The vertical acceleration of the car body is more sensitive to the tooth crack. Jiang *et al.* [40,41] investigated the vibration characteristics of gear fault in the railway locomotive dynamics system using a spatial dynamics model of a heavy-haul electric locomotive that accounted for the dynamic coupling effect of the gear transmission system. The main findings of their research are that the time–frequency analysis of the dynamic meshing force, as well as the vertical and longitudinal vibration acceleration of the wheelset, can reveal the fault characteristic frequency resulting from tooth root cracks. Additionally, the fault vibration caused by tooth root crack is difficult to transfer to the bogie frame due to the primary suspension system. Condition indicators such as Fourth Order Figure of Merit (FM4), M6A, and M8A were found to reflect the influence of crack depth on the dynamic characteristics of the system. The effects of crack depth on the FM4, M6A, and M8A values for longitudinal and vertical vibration accelerations of wheelsets are similar. Chen *et al.* [42] studied the evolution law of the dynamic response characteristics of the vehicle–track system under the influence of tooth root cracks. The results indicate that the fault features associated with tooth root cracks can be obscured by intensified vibrations. To enhance and extract the fault features, the author proposed a signal processing technique that combines the angular synchronous average technique with statistical indicators calculated from the data series constructed from the frequency spectrum. The statistical indicators M8A, calculated from the motor vibration signal, demonstrated the highest sensitivity to the development of pinion tooth root crack faults. Additionally, Li *et al.* [43] studied the crack propagation characteristics of high-speed train gears. They developed a finite element model of a helical gear pair with a crack at the tooth root using ABAQUS software. The study examined the growth trajectory and propagation life of the crack at the tooth root. As the load increases, the crack propagation life decreases significantly. This suggests that acceleration or braking conditions impose higher loads on the gear system and can significantly reduce the life of the crack propagation process.

The above research studies not only revealed the evolution law of the fault but also put forward fault indicators for fault identification, which serves as a solid foundation for subsequent fault diagnosis. The actual operation of railway rolling stock is more complex and can be influenced by factors such as wheel polygonization and wheel flat. These factors make the extraction of fault features more challenging. The fault vibration characteristics of the gear transmission system under the excitations, such as wheel polygonization and wheel flat, need further investigation.

2) HOUSING CRACK. In railway vehicle gearbox, housing crack is one of the most common faults. The gearbox is prone to abnormal vibrations and fatigue damage caused by internal and external excitations, including coupling excitation [45]. Designers consider the static strength and stiffness of the gearbox but tend to ignore the fatigue strength [46]. As mentioned in the introduction, several train series in China have encountered gear crack or fatigue crack in their gearbox. The gearbox housing of Portuguese Railways' 2600 series locomotives has also experienced the failure of the gearbox housing [47]. This series of locomotives appeared to have cracks in the upper area of the cover and in the frontal central area of the body of the housing [47].

Fatigue failure is the leading cause of mechanical structural failure. When the material or structure is subjected to repeated changes in load, the mechanical structure may fail even if the stress value has not exceeded its strength limit or is lower than the elastic limit. This phenomenon, known as fatigue failure, occurs when a material or structure fails under the repeated action of alternating loads. Vibration fatigue generally includes resonant fatigue and nonresonant fatigue. The structural resonance caused by the alternating load can lead to fatigue fractures at the locations of local stress concentration or weak positions [48]. The dynamic characteristics of the gearbox in railway vehicles indicate that it is prone to resonance when subjected to internal and external excitations, as well as coupling excitation.

To investigate the impact of wheel polygonization on the fatigue of the gearbox housing mounted on the wheelset of a high-speed train, Wu *et al.* [49] established a three-dimensional multibody system railway vehicle model, as shown in Figs. 6 and 7. Through the finite element and multibody dynamics analysis, the authors studied the dynamic stress distribution on the gearbox housing caused by variable amplitude polygonal wear on the wheel. Using the Kernel density estimation method, the authors extrapolate the dynamic stress on the gearbox to estimate the stress levels after a total running distance of 140,000 km. They then estimate the fatigue damage. The results show that the fatigue damage with a 20th-order polygonal wear is 63% higher than without the polygonal wear on the wheel. Wheel polygon wear significantly reduces the lifespan of the gearbox housing. Li *et al.* [50] carried out a macro-analysis of the crack in the gearbox fracture section and identified that the fatigue crack initiates at the inside corner

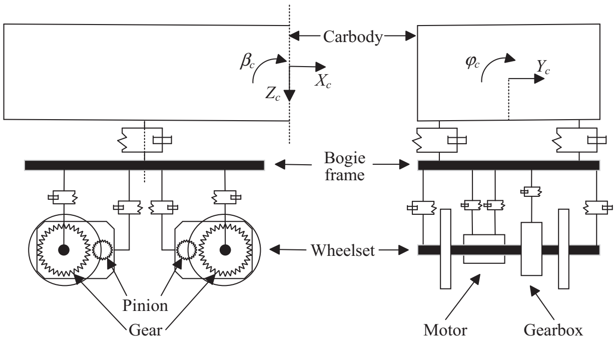

Fig. 6. Railway vehicle dynamics model [49].

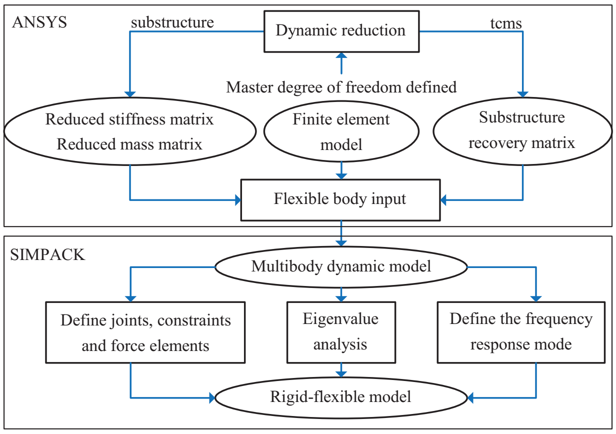

Fig. 7. Rigid–flexible modeling framework [49].

of the gearbox. The results of the online test indicate that the exciting frequency resulting from line turbulence can cause resonance in the gearbox housing, leading to high dynamic stress amplitude and, ultimately, fatigue cracks in the gearbox housing. Wang *et al.* [51] established an equivalent stress and fatigue strength interference reliability model for the railway vehicle gearbox. They also investigated the relationship between the fatigue reliability of the gearbox housing and the service mileage. The stress level of the gearbox housing increases with higher train speed and motor output torque. Moreover, improvements in the casting quality of the aluminum alloy housing have led to an extended lifespan of the gearbox housing. For example, the service mileage can be increased by a factor of 3.8 when the casting pore size changes from 0.9 to 0.5 mm in diameter. He *et al.* [52] developed a method to analyze and assess the strength and fatigue characteristics of transmission gearbox in high-speed trains. This method was applied to a series of high-speed gearboxes, and its accuracy was verified through running tests.

3) GEAR SPALLING. Due to frequent and high-load gear meshing, gearboxes are prone to contact fatigue, which can result in failures such as spalling. After a long period of service, the rail vehicle traction transmission system is prone to gear spalling, as shown in Fig. 8. This issue diminishes the operational performance of the railway vehicle. Lin *et al.* [53] conducted a study on the dynamic characteristics and fault mechanism of gear tooth spalling in railway vehicles. Theoretically, gear spalling generates sidebands in the meshing frequency. However, the time–frequency spectrum analysis reveals that gear tooth spalling does not exhibit a significant sideband in the operating environment of railway vehicles. This phenomenon could be attributed to the strong noise and nonstationary environment. The author found that the length and depth of spalling affect the amplitude of the time-varying meshing stiffness, while the width determines the range of the time-varying meshing stiffness loss. In low-noise environments, the crest factor is the most effective evaluation indicator. In strong noise, applying a high-pass filter allows the root mean square and variance to exhibit excellent classification capabilities, unaffected by the vehicle's speed.

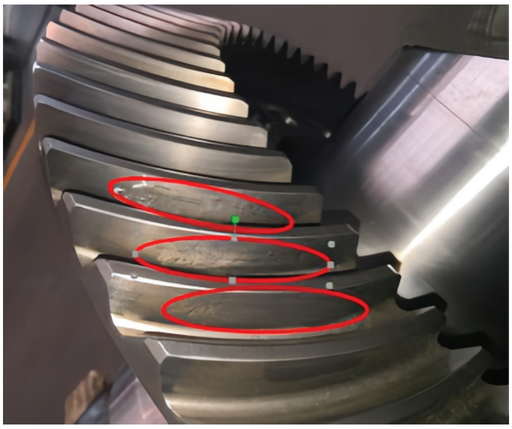

Fig. 8. Teeth spalling on the driven gear [54].

4) GEAR WEAR. Friction damage to the material frequently occurs on the contact surface of gear teeth during the meshing process. Inappropriate gear material, the presence of hard particles between contact surfaces, and insufficient or contaminated lubricating oil supply can lead to early gear wear, as shown in Fig. 9. Gear wear alters the size of the contact surface and the tooth shape of the gear, and severe wear results in gear failure. To investigate the nonlinear dynamics of high-speed multiple units gear transmission system with wear faults, Yang *et al.* [55] developed a dynamic model of helical gears with wear fault and analyzed the dynamic response. During the initial stage of the fault, wear failures have the most significant influence on Root Mean Square (RMS), kurtosis, and peak-to-peak values. As the wear area continues to increase, all these indicators fluctuate with a small amplitude. Vibration signals can be used to identify and diagnose the wear fault. Liu *et al.* [38] found that when the surface of the driving gear is slightly worn, the time–domain response of the driven gear node exhibits an obvious periodic pattern corresponding to the rotation period of the worn gear shaft. The vibration amplitude of the vertical response of the driven gear nodes increases, and the gear fault frequency is mainly concentrated in the gear meshing frequency band.

5) MISALIGNED CARDAN SHAFT. The cardan shaft is a specially designed component in the CRH high-speed train. It connects the drive motor to the gearbox and transmits the traction force. Due to its role in coordinating complex motion relationships, its failure may lead to the failure of the gearbox. An example of a failed gearbox discovered during maintenance is shown in Fig. 10. Hu *et al.* [57] investigated how a misaligned cardan shaft could result in

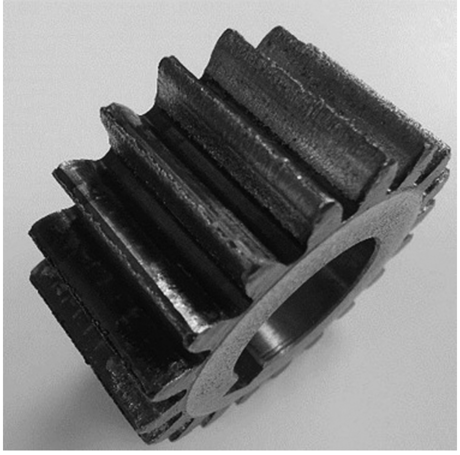

Fig. 9. Extremely worn gear [56].

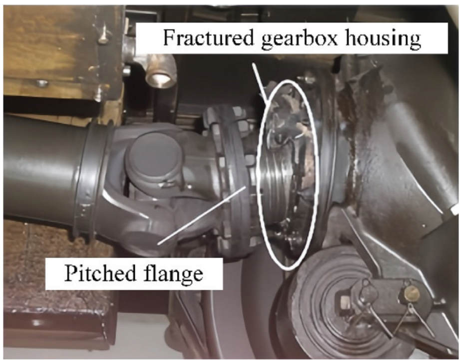

Fig. 10. Fracture failure of gearbox [57].

the failure of the gearbox in the CRH high-speed train. First, theoretical kinematic analysis is conducted to determine the kinetics and dynamics of a misaligned cardan shaft. Then, numerical simulations are used to calculate the inertial force and frictional force experienced by the misaligned cardan shaft. Inertial forces led to a significant bending load on the flange and bevel gear shaft, resulting in vibration of the bevel gear shaft. Since the distance between the flange and the gearbox housing is small, the vibration will cause an impact between them. The collision between the flange and the gearbox, caused by the vibration, is the main reason for the enlargement of the interference fit of the shaft and fracture of the gearbox housing.

6) GEAR ECCENTRICITY. Gear eccentricity refers to the misalignment of the gear center with the center of the rotating shaft, often resulting from assembling errors. Wang *et al.* [58] studied the coupled torsion vibration responses of a transmission system in a vehicle–track vibration environment. The results show that the traction torque and gear eccentricity have an impact on the gear meshing, vibration amplitude, and frequency doubling during vehicle acceleration. When the train is running at high speed, gear eccentricity has a significant influence on the torsional vibration of the system. It increases the amplitude of dynamic mesh force and wheel–rail longitudinal creep force. The frequency components of the system include the shaft frequency, gear mesh frequency, and their modulation frequencies.

7) GEARBOX BEARING FAULT. Due to the forced vibrations and the induced coupled vibrations with gears, gearbox bearings are prone to failure. The rolling bearing failure can generate high-frequency pulse vibrations at high speeds, resulting in high-frequency components in the vibration of the gearbox. Consequently, it is essential to investigate the vibration characteristics of the gearbox with bearing faults. Cai *et al.* [59] established a novel dynamics model of high-speed train bearing-gear system. The results show that the bearing fault can cause high-frequency vibration, significantly affecting gearbox vibration and potentially leading to resonance in the gearbox housing. Moreover, the bearing fault greatly affects the vibration amplitude of gear meshing components and increases the number of reverse gear engagements, thereby affecting the stability of the gear pair, as observed in the phase diagram.

The types of faults that have been studied are shown in Table I. The extensively studied fault types are gear tooth crack and housing crack, which have provided insights into the causes of gearbox failure and the vibration characteristics exhibited during failure. However, there is a need for further comprehensive investigation of gear spalling, gear wear, and gear eccentricity. Additionally, there is a lack of studies on the vibration characteristics of faulty gearboxes with multiple coexisting faults or under the influence of both internal and external excitation. Furthermore, most of these studies are based on dynamics models and lack further verification through experimental or measured data.

To provide a better overview of the current state of research on the dynamics of railway vehicle gearboxes, we have further summarized the existing research findings in Table II based on three aspects: research topics, research methods, and research models. The research topics include vibration characteristics, stress analysis, chaotic characteristics, electromechanical coupling vibration, and fault characteristics. The main methods used in the study of gearbox dynamics are lumped parameter method (LPM), finite element method (FEM), test method (TM), and their hybrid approaches. The methods for calculating the time-varying mesh stiffness of gears include analytical methods (AMs) and finite element analysis. For research models, we categorize them into three main types. The first type of model establishes a comprehensive dynamic model of the vehicle, which includes not only the gear transmission system but also other components such as the frame and car body. We refer to this as the dynamic model of high-speed train/locomotive with gear transmission system. The second type of model is the dynamic model of only the gear transmission system, which we refer to as the dynamics model of the high-speed train/locomotive gear transmission system. On the basis of the first type of model, when the track is included, it is the third type of model, which we refer to as the vehicle–track coupling dynamics model of high-speed train/locomotive with the gear transmission system. The final summary is presented in Table II.

III. FAULT DIAGNOSIS OF RAILWAY VEHICLE GEARBOX

The fault diagnosis of gearboxes has garnered significant attention, resulting in numerous research findings [60]. In general, the fault diagnosis of the gearboxes can be achieved by analyzing signals that can reflect the state of the gearbox, such as vibration, temperature, current, and acoustic emission signals. However, many existing studies on gearbox fault diagnosis may not be directly applicable to railway vehicle gearboxes due to the complex operating conditions and diverse external excitations they experience. In this section, we broadly categorize the fault diagnosis methods into: signal processing and artificial intelligence.

A. SIGNAL PROCESSING ALGORITHMS

Signal processing is a widely used method for fault diagnosis. It extracts fault features from the signal for fault diagnosis. Due to the high levels of noise and nonstationary environment, we require advanced signal processing technologies to handle vibration signals effectively. Wan *et al.* [61] applied the ensemble empirical mode decomposition (EEMD) and Hilbert transform (HT) methods to achieve the fault diagnosis of the high-speed train gearbox. The proposed method exhibits superior performance compared to the continuous wavelet transform method. In the online running tests of the locomotive, the method successfully diagnosed the fault of the driving gear. Chen *et al.* [54]

Table I. Summary of existing fault studies

Fault type	Authors	Year	Summary
Gear tooth crack	Wang *et al.* [37]	2020	When gear tooth crack failure occurs, the vibration amplitude of the gear system increases. Additionally, the vibration energy distribution of the rotor system shifts to lower resonance frequency bands, and the gear meshing frequency band exhibits obvious modulation phenomena. The time–frequency analysis results of dynamic mesh forces, wheelset longitudinal, and vertical vibration accelerations can reflect the fault vibration characteristic frequency.
	Liu *et al.* [38]	2022	
	Liu X, Sun Q, Chen C. [39]	2018	
	Jiang *et al.* [40,41]	2020 2018	
	Chen *et al.* [42]	2019	
	Li *et al.* [43]	2017	
Housing crack	Morgado T L M, Branco C M, Infante V. [47]	2006	The gearbox undergoes local resonance due to track excitation, leading to higher dynamic stress amplitudes in specific areas of the housing and resulting in cracks. Moreover, the service life of the gearbox housing is significantly reduced due to the impact of wheel polygonal wear.
	Wu *et al.* [49]	2019	
	Li *et al.* [50]	2017	
	Wang *et al.* [51]	2018	
	He *et al.* [52]	2018	
Gear spalling	Lin *et al.* [53]	2023	From the time–frequency spectrum of the gearbox housing vibration, gear tooth spalling may not exhibit prominent sidebands. Effective denoising and weak feature extraction algorithms are needed to extract its characteristic frequency accurately.
Gear wear	Yang *et al.* [55]	2019	From the spectrum of gear vibration, the gear fault frequency is mainly concentrated in the gear meshing frequency band. Wear failures have the greatest impact on RMS, kurtosis, and peak-to-peak values at the initial failure stage.
	Liu *et al.* [38]	2022	
Misaligned cardan shaft	Hu Y, Lin J, Tan A C. [57]	2019	A misaligned cardan shaft can result in vibration of the bevel gear shaft, leading to impacts between the flange and the gearbox housing. This can ultimately result in fracture of the gearbox housing.
Gear eccentricity	Wang *et al.* [58]	2021	Gear eccentricity increases the amplitude of dynamic mesh force and wheel–rail longitudinal creep force.
Gearbox bearing fault	Cai *et al.* [59]	2020	Bearing fault can cause high-frequency vibration and lead to resonance in the gearbox housing, thereby increasing the vibration amplitude of the gear meshing components.

aimed to address the drawback of the mode-mixing problem in the empirical mode decomposition (EMD) method and proposed the complementary ensemble empirical mode decomposition (CEEMD). However, the computational cost of this method is too high. Therefore, the author further improved CEEMD to reduce the computational requirements and proposed the intrinsic mode functions (IMFs) evaluation index for selecting IMFs automatically. This method was validated using vibration signals from in-service high-speed train gearboxes, and it successfully diagnosed the continuous teeth spalling and poor lubrication. Ren *et al.* [62] presented a method of adaptive time-varying blind separation based on variable metric empirical mode decomposition (VMEMD). The fault sources were separated through sparseness and iterative screening. Then, the optimal IMF was obtained by adjusting the time span. Experimental analysis shows that the method can quickly and accurately extract fault features even under a low signal-to-noise ratio. This method can be utilized for state detection and fault diagnosis in railway transportation. Based on the Wiener state degradation process and multi-sensor filtering, Cheng *et al.* [63] proposed a fault diagnosis method for a running gear system. Considering the information acquisition and transfer characteristics of the composite sensors, the author first established the distributed topology of the axle box bearing. Second, a distributed filter is built based on the bilinear system model. Then, they built a nonlinear degradation model of Wiener process considering the factor of temperature. Finally, the fault diagnosis threshold is determined according to Chebyshev's inequality. In the case study, the effectiveness of the proposed method is verified using an open dataset of rotating machinery bearings and temperature data from a high-speed rail running gear system. To deal with the non-Gaussian measurement and slow-change faults in running gear systems, Cheng *et al.* [64] proposed a time-series independent component analysis method for fault detection. The proposed method successfully detects faults in the motor, bearing, and pinion box and has a stronger ability to detect early faults than other methods. Hu *et al.* [64] introduced a segmentation algorithm based on cubic spline interpolation, which effectively suppressed impact response signals caused by rail joint gaps. This algorithm segmented a single large sample signal into multiple short-term sample signals, allowing for accurate extraction of useful short-term signal samples for fault diagnosis.

The gearbox input shaft is coupled with the motor's output shaft, and faults in the gears will also be reflected in the motor's current and torque. Therefore, the fault diagnosis can also be carried out based on the motor current. Henao *et al.* [65] investigated the effect of output gear tooth damage and surface wear faults on the stator current and estimated electromagnetic torque. The results show that both the stator current and the estimated electromagnetic torque can better indicate the gearbox faults. Therefore, they can be used for fault diagnosis of railway vehicle

Table II. Dynamics research summary on railway vehicle gearbox

Research topic	Research method	Research model	Reference
Vibration characteristics	LPM, FEM	Model A	[13,17,19]
		Model B	[14]
		Model C	[26,29,36]
	LPM, AM, TM	Model B	[16]
		Model C	[23,31]
	TM	/	[18,20]
	LPM, FEM, TM	Model B	[21]
	LPM, AM	Model a	[22]
		Gear-bearing-track coupling dynamics model of the high-speed train with gear transmission	[24]
Stress analysis	LPM, FEM	Model C	[25,28]
	FEM, TM	Model A	[27]
	TM	/	[30]
Chaotic characteristic	LPM	Model B	[15]
		Model b	[32,33]
Electromechanical coupling vibration	Electromechanical co-simulation	Model c	[34,35]
Fault characteristics	LPM, AM	Model b	[37]
		Model B	[38,55]
		Model a	[39–42,53]
	FEM	Finite element model of high-speed train gear pair	[43]
		Model B	[52]
	TM	/	[47,50,51]
	LPM, FEM	Model A	[49]
		Model C	[58,59]
	LPM, TM	Dynamics model of misaligned cardan shaft	[57]

[*] Model A/a refers to the dynamic model of high-speed train/locomotive with gear transmission system; Model B/b refers to the dynamics model for high-speed train/locomotive gear transmission system; Model C/c refers to the vehicle–track coupling dynamics model of high-speed train/locomotive with gear transmission system.

gearboxes. In fact, a local fault in the gear causes torque oscillations that modulate the frequency component of the stator current signal and generate sidebands in the power spectrum of the stator current. Hence, Zhang *et al.* [66] proposed a fault diagnosis method based on wavelet energy entropy and dual-tree complex wavelet transform. The wavelet energy entropy can be used for a preliminary diagnosis of the signal, while the dual-tree complex wavelet transform can provide further insight into the fault type. Similarly, based on the current signal, Zhang *et al.* [67] proposed a fault diagnosis method for locomotive gear based on wavelet bispectrum (WB) and wavelet bispectrum entropy. Since the motor current in a faulty gear system contains not only fault-related frequency information but also power supply frequency and gear meshing-related frequency, extracting the fault frequency from it is challenging. So, the author developed an innovative method based on the WB to extract the characteristic frequency of the fault.

Gearbox fault monitoring can be conducted using vibration, temperature, and current signals. Temperature signals can indicate the overall operation state of the gearbox but are hard to tell specific types of faults. The fault diagnosis method of railway vehicle gearbox based on motor stator current signal analysis does not need additional sensors, which is more cost-effective and convenient for continuous monitoring in railway vehicles [67].

However, existing fault diagnosis methods based on signal processing algorithms can only identify the type of fault and do not provide a quantitative assessment of the fault severity. This aspect should be considered in future research to enhance the accuracy and effectiveness of fault diagnosis in gearbox systems.

B. ARTIFICIAL INTELLIGENCE ALGORITHMS

In recent years, there has been significant progress in the development of AI-based methods in fault diagnosis. The AI methods include belief rule base (BRB), extension theory, and machine learning methods such as convolutional neural network (CNN), support vector machine (SVM), and hidden Markov models.

Based on belief rule base with mixed reliability (BRB-mr), Cheng *et al.* [68] proposed a fault diagnosis method. This model considers two types of interference factors that affect the observed data in engineering practice: the performance of the sensor and the influence of the external environment. This method quantifies the unreliability information in a reasonable manner. The effectiveness and feasibility of the proposed method have been verified through numerical analysis and experiments conducted on a running gear system. Furthermore, the diagnosis method is validated to have higher fault diagnosis accuracy compared to existing methods, such as BRB, back-propagation neural network, decision tree, and SVM. Similarly, the authors combined deep slow feature analysis with the belief rule base method and proposed a data-driven fault detection and diagnosis method for the high-speed train running gears [69]. The superiority of the method is proven by the running gear test of the high-speed train.

In addition to the aforementioned belief rule base method, machine learning methods have also been employed in the fault diagnosis of railway vehicle gearboxes. For the diagnosis of gear tooth faults, Wang *et al.* [70] propose an ensemble decision approach that combines the dislocated time–frequency representation and a pretrained CNN. The experimental results show that the method is applicable and effective in the variable working condition of the railway vehicle gearbox. He *et al.* [71] utilized the EEMD and local linear embedding to extract key features. The SVM was subsequently used to achieve high performance of fault diagnosis on the gear. The analysis results demonstrate that the proposed method can effectively detect gear wear, crack, and broken teeth. The detection rate is 5% higher compared to the existing methods, such as the linear feature extraction methods. As shown in Fig. 11, Liu *et al.* [39] used the principal component analysis (PCA) and the grey relational analysis methods to detect the degree of tooth root crack damage in the locomotive gear transmission system. First, the multidimensional characteristic parameter matrix is established by calculating various indicators of vertical vibration of the vehicle body. Then, the dimension of the matrix is reduced using PCA. Finally, the degree of tooth root crack damage is detected using the grey relational analysis method. In addition to detecting gear faults, the diagnosis of internal defects in the gearbox shell has also been studied. In order to detect internal defects in the gearbox shell of high-speed trains during product testing and maintenance inspections, Ai *et al.* [72] proposed the Adaboost_BTSVM algorithm. This algorithm aims to achieve automatic classification of casting defects in the gearbox shell of high-speed trains. In this method, three-dimensional computed tomography (CT) technology is used to obtain the three-dimensional data of the gearbox shell. These data are then used to train the classification model Adaboost_BTSVM. The trained model can achieve the automatic classification of casting defects in the high-speed train gearbox shell. Ai *et al.* [73] collected the acoustics emissions signals and tensile damage data through tensile tests. Then, feature extraction techniques were applied to capture the characteristics of the tensile damage process. Subsequently, SVM and weighted SVM were utilized to identify different stages of tensile damage in the gearbox shell of high-speed trains.

When labeled data are not available, fault detection algorithms become more applicable. Cheng *et al.* [74] proposed a new test statistic based on the Hellinger distance and slow feature analysis, which can be utilized to detect incipient faults in running gear systems. The authors proposed hidden Markov methods for performing reliable fault diagnosis tasks. The proposed method not only has a good fault detection ability but also exhibits strong robustness to high-level noise. Song *et al.* [75] introduced the dynamic inner into the framework of multiple statistics and proposed a dynamic inner slowness feature analysis method for the fault detection of running gear systems. This method improves the detection speed and the detection rate of slow-change faults. To monitor the abnormal vibrations in the gearbox, Yao *et al.* [76] proposed a joint algorithm of self-learning and fuzzy clustering algorithm, as shown in Fig. 12. A mechanical vibration test rig was built to verify the joint algorithm. The experimental results show that the new method can efficiently identify abnormal vibrations when mechanical failure occurs. Liu *et al.* [77] proposed a method based on the extension theory for monitoring the running condition of high-speed rail vehicle gearboxes. By extracting appropriate characteristic parameters, the matter-element model of the gearbox under normal working conditions is established. The particle swarm optimization algorithm was utilized to optimize the characteristic parameters of the classical domains of the matter-element model. Based on the matter-element model and the dependent function, the author achieves the monitoring of the running status of the high-speed railway gearbox. Liu *et al.* [78] initiated their study with time-series forecasting models and introduced a vibration signal prediction model based on EEMD, autoregression (AR), and support vector regression (SVR). Initially, the EEMD method is used to decompose the signal. Subsequently, an AR model and SVR are employed to predict each IMF. Finally, the two predictions are weighted and summed together, and the weights are optimized by the chaos particle swarm optimization algorithm. The proposed method is expected to be applied to the assessment of the running state of a high-speed train gearbox.

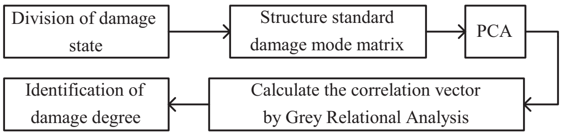

Fig. 11. Flow chart of detecting the degree of tooth root crack damage [39].

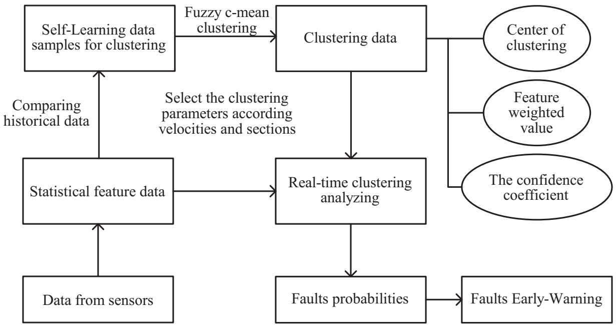

Fig. 12. The abnormal vibration of the gearbox monitor [76].

Existing studies, such as [69,74–79], primarily focused on monitoring the overall health status of gearboxes rather than specifically identifying the faulty components. Future research on diagnosing the specific fault types and degrees in gearboxes is needed. Additionally, there is a lack of research on the application of artificial intelligence algorithms for diagnosing gearbox faults using current signals in railway vehicles.

C. SUMMARY

(1) As shown in Table III, both signal processing and artificial intelligence methods have yielded significant research findings in the field of railway vehicle gearbox fault diagnosis.

Table III. Fault diagnosis of railway vehicle gearbox

Technology category	Authors	Key techniques	Signal type
Signal processing algorithms	Wan *et al.* [61]	Ensemble empirical mode decomposition, Hilbert transform	Vibration
	Chen *et al.* [54]	Complementary ensemble empirical mode decomposition	Vibration
	Ren *et al.* [62]	Variable metric empirical mode decomposition	Vibration
	Cheng *et al.* [63]	Wiener state degradation process, multi-sensor filtering	Temperature
	Cheng *et al.* [79]	Time-series independent component analysis	Temperature, current
	Hu *et al.* [64]	Cubic spline interpolation	Vibration
	Zhang *et al.* [66]	Wavelet energy entropy, dual-tree complex wavelet transform	Current
	Zhang *et al.* [67]	Wavelet bispectrum (WB), wavelet bispectrum entropy	Current
Artificial intelligence algorithms	Cheng *et al.* [68]	Belief rule base, Dempster–Shafer theory	Temperature
	Cheng *et al.* [69]	Deep slow feature analysis, belief rule base	Vibration Temperature
	Wang *et al.* [70]	Dislocated time–frequency representation, convolutional neural network	Vibration
	He Xiaoqin and Chang Youqu [71]	Empirical mode decomposition, local linear embedding, support vector machine	Vibration
	Liu *et al.* [39]	Principal component analysis, grey relational analysis	Vibration
	Ai *et al.* [72]	Adaboost_BTSVM algorithm	Three-dimensional CT data
	Ai *et al.* [73]	Weighted support vector machines	Acoustic Emission
	Cheng *et al.* [74]	Hellinger distance, slow feature analysis, hidden Markov	Temperature
	Song *et al.* [75]	Slow feature analysis	Temperature Vibration
	Yao *et al.* [76]	Self-learning, fuzzy clustering algorithm.	Vibration
	Liu *et al.* [77]	Extension theory	Vibration
	Liu *et al.* [78]	Ensemble empirical mode decomposition, autoregression, support vector regression	Vibration

(2) The primary focus of fault diagnosis for railway vehicle gearboxes is on gear fault diagnosis. The main types of signals are vibration signals, current signals, acoustic emission signals, and temperature signals. Signal processing methods mainly include EMD and various time–frequency analysis methods. Research of fault diagnosis based on artificial intelligence algorithms is relatively extensive. These methods are primarily used for condition assessment and abnormal monitoring.

(3) These fault diagnosis methods seldom consider the influence of track irregularity, wheel out of round, wheel flat, and so on. Moreover, those methods seldom account for variable working conditions, which suggests that these methods may lack robustness.

(4) The applications of signal processing methods depend on various parameter choices and expertise experience, which limits their applications. The development of intelligent diagnosis algorithms is a prominent research area for railway vehicle gearboxes in the future. Although traditional intelligent algorithms are currently employed for fault diagnosis in railway vehicle gearboxes, it is worthwhile to explore the application of more advanced and cutting-edge algorithms in this field.

IV. RESEARCH PROSPECTS

Compared to other key components of vehicles, such as the motor, axle box bearings, and wheels, research on vehicle gearboxes is relatively limited. However, with the increase in train speed, the operating environment of the gearbox deteriorates. Therefore, it is necessary to study the condition monitoring and fault diagnosis technology for railway vehicle gearboxes. Due to the complex structure and operating environment of the gearbox, there are still some difficulties and technical bottlenecks that need to be overcome in the existing dynamics research and fault diagnosis technology.

(1) To speed up the simulation, some components, such as wheels and housing, will be set as rigid bodies in the existing dynamic models. However, this may result in the omission of crucial information in the simulation results. Therefore, it is necessary to further develop a rigid–flexible coupling dynamics model that can better reflect realistic information.

(2) Temperature and acoustic emission signals are useful for fault diagnosis. However, studies on the thermodynamic coupling and acoustic vibration coupling of gearboxes were not enough.

(3) A gap exists between fault mechanisms and fault diagnosis in the context of rail vehicles. The complex

operating conditions of rail vehicles make it challenging to establish a clear mapping relationship between gearbox faults and external responses. Limited research progress has been made in understanding fault initiation and dynamic fault evolution mechanisms, resulting in a lack of fundamental theoretical support for early fault detection, composite fault analysis, and remaining useful life prediction. The latest simulation studies can lean toward composite fault scenarios and full-life simulations, providing more theoretical support for gearbox fault diagnosis, condition monitoring, and life prediction.

(4) The reported methods for diagnosing gearbox faults mostly rely on common approaches. It is meaningful to incorporate more advanced and cutting-edge signal processing or artificial intelligence algorithms into railway vehicle gearbox fault diagnosis.

(5) Most of the existing fault diagnosis methods focus on stationary working conditions and rarely consider the influence of track irregularity, wheel out of round, wheel flat, and variable working conditions. It is meaningful to further study these influences to improve the robustness and versatility of these methods, so that the diagnosis methods become more practical.

V. CONCLUSION

The gearbox of the railway vehicles is a crucial component of the bogie, ensuring the smooth operation of the vehicles. In this paper, the vibration characteristics of the gearbox under internal and external excitation and fault conditions are summarized. Additionally, the method and research status of fault diagnosis of railway vehicle gearboxes are reviewed in detail. Although the existing research results are extensive, they are somewhat disconnected from practical applications. Additionally, there are still technical difficulties and bottlenecks that need to be addressed. Considering the complexity of the actual working environment of railway vehicle gearboxes, future research should focus on practical applications, developing dynamic models that accurately reflect the vibration characteristics of railway vehicle gearboxes and validating the fault diagnosis methods using data collected from real trains. With the development of signal processing techniques and artificial intelligence, more advanced fault diagnosis technologies should be developed to meet the high accuracy and real-time requirements of railway vehicle fault diagnosis, and advanced fault prediction techniques or residual life prediction techniques could be developed in the future. Simultaneously, the integration of dynamic research with fault diagnosis research is essential, as dynamic research can guide the development of fault diagnosis techniques. Dynamic models also have the potential to be combined with data-driven approaches to develop holistic health management technologies for railway vehicle gearboxes throughout their life cycle.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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