Mechanical Systems and Signal Processing 115 (2019) 29–44

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Vibration feature evolution of locomotive with tooth root crack propagation of gear transmission system

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ARTICLE INFO

Article history:
Received 31 January 2018
Received in revised form 1 May 2018
Accepted 21 May 2018

Keywords:
Tooth crack
Gear mesh stiffness
Train
Fault vibration characteristic
Rail irregularity

ABSTRACT

As the prompt development of modern railway transportation towards high-speed and high load-capacity, the high-power locomotive is urgently required. Under this situation, the wheel–rail dynamic interaction is becoming more and more intensified which will deteriorate the vibration condition of the key elements of locomotive, such as the gear transmissions. Once gear failures are present, such as gear tooth crack or breakage, it is likely to threaten the operation safety of the locomotive. Thus, deep insight into the fault features of the locomotive gear transmission is urgently necessary for prevention of the induced disastrous consequences. This paper is concentrated on the fault vibration feature extraction of a locomotive in presence of gear tooth root crack under the complicated dynamic excitations from both the gear transmissions and the nonlinear wheel–rail interactions. The locomotive–track coupled dynamics model considering the dynamic effect of the mechanical power transmission path is employed, and the time-varying mesh stiffness of the gear pair with tooth root crack fault and the rail geometric irregularities are then incorporated into the dynamics model to obtain the vibration responses. Then, angular synchronous average technique is proposed to enhance the fault vibration features, and the statistical indicators extracted in frequency domain are developed to reveal the evolution law for the crack propagation scenarios along crack depth or tooth width. The analyzed results indicate that the angular synchronous average technique could effectively reveal the fault vibration feature, and the M8A in the selected statistical indicators is most sensitive to the tooth crack propagation in frequency domain.

1. Introduction

As the key element of railway locomotive, gear transmission plays a vital role in the power delivery between the traction motor and the wheelset during the traction or braking process so as to drag or resist the longitudinal motions of locomotive [1,2]. As the fast development in railway transportation, high power locomotives are urgently required in the process of train speed-up and/or the load capacity extension. Whatever for the high power or the faster operation speed, it will deteriorate the operation conditions of the gear transmissions subsystems due to the more intensified wheel–rail dynamic interactions, which is likely to cause failures to the gear transmissions, such as gear tooth crack and tooth breakage. In fact, these failures of the gear transmissions have been found by the railway administrations in practical operation of locomotives. Once the failures happen to the gear transmission system, its dynamic performance will be degraded, and further it may cause power

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https://doi.org/10.1016/j.ymssp.2018.05.038

interruption or even cause disastrous consequences such as derailment or train crashes [3]. This will bring great challenges to the train operation safety and reliability. Consequently, it is essential to reveal the dynamic performance and fault features of gear transmissions in locomotive for prevention of the induced serious consequences.

In the area of railway vehicle dynamics, some classical railway vehicle dynamics models were developed [4] in the last century where the dynamic interactions between the vehicle and the track systems were usually not considered. In the subsequent research, significance of taking the coupling effects between the vehicle and the track into consideration had been realized since the early 1990s. For example, Zhai et al. [5] established a typical dynamics model (called Zhai model) by regarding the vehicle and the track as an integral system through the wheel–rail nonlinear dynamic interaction. The dynamic interactions between the vehicle and the track structure were then investigated by many scholars at the view point of the systematic idea [6–8]. In the vehicle–track coupled dynamics theory, wheel–rail contact relationship is the kernel which had attracted numerous researchers to work on it since the early of the last century. For instance, the well-known Hertzian nonlinear elastic theory and non-Hertzian contact approaches were developed for wheel–rail normal contact force calculation [5,9]. And until to now, the creep force calculation has always been a hot research topic since the creep phenomenon was observed in 1930s. The most well-known method is the Kalker linear theory [10]. Then, some simplified methods were then proposed so as to improve the calculation efficiency [11,12]. Iwnicki [13] made a detailed review on the methods widely applied to calculate the wheel–rail contact forces.

However, only very limited work were on the investigation of the traction system dynamic performance of railway vehicles. Hirotsu et al. [14] established a single-wheelset dynamics model for a parallel cardan drive system to reveal the self-excited vibrations properties due to slippage. Considering the electrical and mechanical environment of the inverter-driven railway electric vehicle, Kim et al. [15] developed an electro-mechanical re-adhesion control simulator. Kia et al. [16] found that the dynamic performance of the railway mechanical traction system has important effect on the motor current signature in his reduced scale experimental tests. Yao et al. [17] investigated the stability and characteristics of locomotives stick–slip vibrations under saturated adhesion with using a simplified single wheel driving system model. Wang et al. [18] analyzed the nonlinear dynamic performance of spur gear transmission system of a locomotive, where the single wheelset dynamics model was employed. In most of these works, many major excitations of the mechanical transmission system, such as the gear mesh excitations and the nonlinear tooth backlash, were usually neglected. Besides, the dynamic interactions between the mechanical transmission subsystem and the vehicle–track coupled dynamics system were usually not taken into consideration. To make up this gap, Chen et al. [1] developed a vehicle–track coupled vertical dynamics model with considering the dynamic effect of the gear transmission system, and the discrepancies between this model and traditional model without gear transmission were revealed. Based on this dynamics model, they [2,19] further established the vehicle–track coupled vertical-longitudinal dynamics model to investigate the dynamic performance of locomotive under tractive and braking conditions. Their dynamics models enable the possibility of simulating the vibration feature of the gear transmission in presence of gear faults.

Up to now, there are still very limited literatures found for the investigation of locomotive gear fault diagnosis. The major discrepancy of the railway locomotive from other machines or mechanical equipment lies at the complicated wheel–rail contact interface, through which most of the major influencing factors excite the vibrations of the vehicle–track coupled dynamics system, such as wheel out of roundness, rail geometric irregularities, rail surface defects, discretely distributed sleepers, roadbed settlement. The vibration energy excited by these factors is usually much greater than that excited by the fault in gear transmissions, especially for the incipient gear fault. In other words, the signal-to-noise ratio is low where the gear fault feature is usually submerged in the strong background noise. How to extract the fault features of the gear transmission system precisely also remains to be the great challenge to the condition monitoring and fault diagnosis of railway locomotives. It is meaningful to carry out the theoretical investigations on fault vibration features of the locomotive gear transmissions, which could assist the development of effective gear fault diagnosis techniques.

Fortunately, there have been numerous works about the gear fault simulation and vibration signal processing techniques for gear transmission systems in many areas, such as the automobile, aerospace, machine tool. Chen and Shao [20] proposed an analytical calculation model for spur gear mesh stiffness with non-uniformly distributed tooth root crack along tooth width. And further they [21] proposed a more general method for total mesh stiffness calculation where the tooth profile deviations were considered. And then the traditional tooth fillet-foundation stiffness method for healthy gear was extended to be suitable for the tooth root crack cases by Chen et al. [22]. Mohammed et al. [23] improved the model proposed in [20] by replacing the line limit with a parabolic curve limit to remove crack-related material from the tooth so as to obtain a higher calculation accuracy for big cracks. And then Chen et al. [24] proposed a simpler line type limit instead of the parabolic curve limit for the crack-related material while keeping the similar accuracy. Liang et al. [25] established an analytical spur gear mesh stiffness calculation method with tooth root crack considering the deviation between the root and the base circles. Ma et al. [26] compared three mesh stiffness calculation methods for spur gear pair with tooth root crack to assess the calculation accuracy. Li et al. [27] verified the mesh stiffness calculation models for three different crack propagation scenarios, namely in the crack depth, the tooth width and the tooth profile directions, by using FE method. Chaari et al. [28] performed the dynamic analysis of the planetary gear set with tooth pitting and cracking faults in both the time and frequency domains. Liu and Shao [29] investigated the vibration features of a bearing using the piecewise response function to reveal the effects from the sharp edge contact deformations of localized defects. Endo et al. [30] introduced a differential diagnosis technique for gear localized faults, namely the tooth surface spall and the tooth root crack, according to their