Effect of wheel polygonization on the axle box vibrating and bolt self-loosening of high-speed trains

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Abstract. The wheel polygonization has become a great concern for the high speed rail vehicle owing to its highly adverse effects in high speed condition. Such periodic distributed wear along the wheel can give rise to high magnitude of high frequency impact loads at the wheel/rail interface and further contribute to severe fluctuations in axle box acceleration and the self-loosening for axle box bolts. In this study, the wheel polygonization-induced axle box vibrations and bolt self-loosening are thus initially investigated through the field tests and the roller test rig. Subsequently, a coupled vehicle/track dynamic model integrating a typical high speed rail vehicle and a flexible slab track is formulated to identify the mechanism of bolt self-loosening in the presence of wheel polygonization. The results suggest that the wheel polygonization can result in high magnitude accelerations in the axle box, and excite some of vibration modes of the axle box and its end cover. The accelerations on the axle box end cover are much larger than those obtained on the axle box, which is also comparable to the experimental results. It is thus believed that the self-loosening of axle box end cover’s bolts is mainly attributed to the severe oscillations on the axle box due to the wheel polygonization.

1. Introduction
The wheel polygonization, referred as continuous uneven wear for the wheel, is a kind of periodic wear on the wheel circumference [1], which has become a great issue for high speed rail vehicle. A typical 20th order wheel polygonization can lead to high magnitude of high frequency wheel/rail impact loads at wheel/rail interface, up to 586 Hz for a polygonal wheel at speed of 300 km/h. Such high frequency impact loads could excite some of vibration modes of vehicle system and pose highly adverse influences on the vehicle performances and running safety. The earlier reports on the wheel polygonization were initially given by Kaper [2] though reviewing the polygonization phenomenon on Netherlands railways. The similar phenomena have also been documented in Germany and France.

Although considerable efforts have been made to investigate the wheel polygonization, the formation mechanisms of wheel polygonization have not yet been explained clearly and the rail vehicles are still subjected to the wheel polygonization-induced problems, such as the self-loosening of the axle box end cover’s bolts. It is reported that the bolts, used to connect the end cover to the axle box, are subjected to loose or even failure in the presence of wheel polygonization, and thereby pose significant effects on the running safety of a high speed rail vehicle. Such adverse influences, therefore, serve as the primary motivation to study the main cause of bolt self-loosening in the presence of wheel polygonization for this study.
Bolt self-loosening, regarded as the major failure form in the bolted connections, is the gradual loss of the preload due to the cyclic external loading. Great efforts thus have been made to study the self-loosening mechanism through the experiments and the analytical models. Earlier investigations on the self-loosening under vibration were reported by Junker [4] via the equilibrium theory considering the Junker connection structure subjected to the lateral load. The investigation also contributes to a bolt loosening test rig. Sakai [5-8] studied the bolt loosening mechanism under the transverse loads and the twisted load via the Junker loosening test rig and the theoretical model, which concluded that the relative sliding between the threaded contact surfaces is the main cause of bolt loosening, and further pointed out that the necessary condition for a bolt self-loosening is that the friction coefficient is smaller than 0.03. The micro-tribology phenomenon between the bolt and the clamped parts also affect the bolt self-loosening [9-13]. Ibrahim [11] suggested that the bolt preload could gradually decrease due to the wear of the contact interface in the vibration environment. The reduction in the preload of bolt simultaneously results in the decrease of the friction coefficient in the contact interface.

Liu et al. [12] experimentally investigated on the loosening mechanism of the bolt connection structure under the axial alternative load. Results suggested that the bolt preload decreases relatively faster in the early stage due to the cyclic plastic deformation, and then followed by the slight reduction in the preload owing to the fretting wear in the later stage. In addition, the lubrication applied in the threads can significantly suppress the bolt loosening. Nassar et al. [13-14] simulated that the plastic deformation of the connecting structure is one of the reasons of the bolt self-loosening in the presence of the axial alternating load. The investigations on the screw-coupling structure under the transverse alternating load [15] indicated that the loosening procedures of the bolt connection structure can be classified into two stages, in which no relative rotation occurs between the bolt and the nut in the first stage, and the slight reduction of preload in the bolt is mainly attributed to the plastic deformation and stress relaxation of the material. However, in the secondary stage, the relative rotation between the bolt and the nut occurs, which is regarded as main contributor of the bolt preload reduction.

In this study, the self-loosening for the axle box end cover’s bolts are initially investigated via the field tests and the laboratory tests. The influences of wheel polygonization are evaluated in terms of the vertical accelerations for the axle box and the axle box end cover and the variations in the bolt preload. In addition, a coupled vehicle/track dynamic model considering the interaction between the bolt and the end cover is further formulated to identify the mechanism of bolt self-loosening.

2. Field tests and Laboratory tests

Figure 1 illustrates the typical axle box end cover used on high speed train. The end cover is made by the glass fiber, and coupled to the axle box via six M8 bolts with the pre-tightening load 12.5 kN. In the operation, the M8 bolt was subjected to the self-loosening and failure, which pose highly adverse effects on the running safety of vehicle. The field test campaign was thus launched to identify the root causes. After the occurrence of bolt failure on the axle box end cover, the profile of corresponding wheels was measured, which suggested that the wheels are subjected to 20th order wheel polygonization with dominating wavelength of about 144 mm along the wheel circumference, and the peak-to-peak amplitude of polygonal wear reaches 0.08 mm approximately, as shown in Figure 2. The on-boarded data acquisition system is employed to continuously record the axle box accelerations at the sample rate of 5000 Hz.

Figure 3 shows the comparisons of the accelerations for the axle box and the end cover of axle box in both lateral and vertical directions. The measurements were obtained at a maximum speed of 300 km/h, which indicates that the axle box end cover was subjected to serve fluctuations in both the lateral and vertical directions. The acceleration amplitudes for the end cover is double that of the axle box, up to 150 g and 100 g for the lateral and vertical directions respectively. The short time Fourier transformation is also employed to demonstrate the vibration transmissions between the axle box and the end cover in both frequency- and time-domain, as shown in Figure 4. The results suggest that both the axle box and the end cover are predominated by the frequency of 586 Hz corresponding to the passing frequency of the 20th order wheel polygonization at 300 km/h. The passing frequency of wheel
polygonization increases in the acceleration phase, and maintains at the frequency of 586 Hz at 300 km/h. Compared to the axle box, the oscillations occurred at the dominant frequency range 500~700 Hz are obviously amplified on the end cover owing to the specific structure and material for the axle box end cover (Figure 1), and the vibration modes of the end cover occurring at the frequencies of about 600 Hz and 700 Hz are also identified, which could lead to the variations in the preload of M8 bolts and further contribute to the self-loosening.

![Axle box end cover](image1)

**Figure 1. Axle box end cover**

![Wheel polygonization with order 20](image2)

**Figure 2. Wheel polygonization with order 20**

![Comparisons of the axle box accelerations and end cover accelerations](image3)

**Figure 3. Comparisons of the axle box accelerations and end cover accelerations, (a) Lateral accelerations, (b) Vertical accelerations**

![Short time Fourier transformation](image4)

**Figure 4. Short time Fourier transformation for the axle box and end cover, (a) Lateral accelerations for the end cover, (b) Lateral accelerations for the axle box, (c) Vertical accelerations for the end cover, (d) Vertical accelerations for the axle box.**

Considering that how much axle box vibrations could lead to the bolt self-loosening, a roller test rig was subsequently developed to investigate the influences of wheel polygonization-induced axle box vibration on the bolt self-loosening, as shown in Figure 5. In the test, both wheels of the roller rig are designed as the polygonal form with wavelength of 140 mm so as to generate the high frequency
impacts for the axle box. The front wheelset is placed on the roller, while another wheelset is clamped on the ground. Two hydraulic actuators are used to apply the half weight of the car body to the bolster. Figure 6 illustrates the acceleration for the axle box and the end cover via the roller test rig at three different speeds (100 km/h, 200 km/h and 300 km/h). It can be seen that acceleration amplitude increases with increased vehicle speed, and the accelerations in the axle box end cover are larger than that of axle box, which is comparable to the measurements of field tests. Dominant frequencies in the short time frequency spectrum, however, suggest that the vibration modes of the axle box and the end cover have not yet been excited at given experiment conditions, which may lead to relatively small acceleration amplitude with respect to the field tests.

The indication of bolt self-loosening can be demonstrated via the acceleration of the end cover under different bolt preloads, as shown in Figure 7. The acceleration of end cover increases with the decreased bolt preload, which further indicates that the self-loosening of bolt is the main contributor of acceleration increasing in the axle box end cover.
3. Theoretical investigation on bolt self-loosening

A coupled vehicle/track dynamic model together with a theoretical model of bolt self-loosening is developed to study the bolt self-loosening mechanism in the presence of wheel polygonization. The vehicle is modelled as a typical high speed rail vehicle consisting of a car body seating on two bogies via secondary suspensions, and each wheelset is coupled to the bogie frame through the coil spring in the vertical direction and the axle box in the longitudinal direction. Considering that high magnitude impact caused by the wheel polygonization could excite some of vibration modes of the wheelset, axle box and the axle box end cover, the modal approach is employed to account for the flexibilities of those components. Furthermore, a theoretical model of bolt self-loosening is formulated to study the self-loosening phenomenon in the bolt, in which the tangential interaction between the bolt washer and axle box end-cover is represented via the Coulomb friction including the nonlinear hysteresis, while the pre-tightening load of bolt is described using a linear spring considering a constant pre-tightening force. The impacts between the bolt and the clamped part when the bolt loosening occurs are described via a nonlinear stop element in the SIMPACK platform, as shown in Fig 8.

![Coupled vehicle/track dynamic model together with a bolt self-loosening model](image_url)

The self-loosening is investigated via the variations of the sliding displacement of the bolt with respect to the end cover considering different bolt preloads, as shown in Figure 9(a). It can be seen that when the bolt preload decreases to 2.5 kN, large variations in the sliding displacements are identified owing to the wheel polygonization-induced oscillations, which suggests that the loss of preload due to the wheel polygonization-induced oscillations is the contributor of bolt self-loosening in the presence of wheel polygonization.

![Bolt self-loosening under the wheel polygonization-induced vibrations](image_url)
4. Conclusion
In this study, the wheel polygonization-induced axle box vibrations and the bolt self-loosening are investigated via the field tests, the laboratory roller rig tests as well as the analytical model. The results suggest that the wheel polygonization can give rise to serve fluctuations in the axle box acceleration, and the oscillations in the axle box end cover are amplified with respect to the axle box owing to its specific material and structure as well as the elastic deformation under the wheel polygonization-induced excitations. The resulting relative sliding between the axle box and the axle box end is regarded as the main contributor of the bolt self-loosening in the presence of wheel polygonization.

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