European Journal of Mechanics A/Solids 61 (2017) 22–34

Contents lists available at ScienceDirect

European Journal of Mechanics A/Solids

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

Dynamics and stability analysis of a freight wagon subjective to the railway track and wheelset operational conditions

M.A. Rezvani*, A. Mazraeh

School of Railway Engineering, Iran University of Science and Technology, Tehran, 16846-13114, Iran

ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form
20 August 2016
Accepted 29 August 2016
Available online 31 August 2016

Keywords:
Axle box clearances
Nonlinear critical speed
Chaotic motion
Coefficient of friction
Three piece bogie

ABSTRACT

In order to enhance railway freight bogie dynamic behavior, a proposal is made for varying the axle box clearances. In essence it introduces nonlinear effects and plays an important role for the bogie dynamic performance. This research involves investigation on the effects of axle box clearances, variation of the wheel-rail friction coefficient and the track curve radius on rail vehicle nonlinear critical speed. Bifurcation diagrams and system dynamic behavior are calculated. Possibility for chaotic solutions and the effect of axle box clearances on bogie curving are also studied. Rail vehicle specifications and the track related parameters originate from real operational conditions. The effects of axle box clearances on wheel wear are examined. The consequences of wheel-rail profile geometry, contact point distribution for various rail inclinations on vehicle curving are considered. The results are debated and recommendations are proposed to improve the vehicle dynamic performance.

1. Introduction

Freight bogies are mainly equipped with frictional dampers. Amongst the methods to improve bogie performance, we propose the introduction of axle box clearances. Adding clearances decreases the bending and shear stiffness of a bogie.

Three piece bogies are widely in use for freight wagons throughout the world. Manufacturing and maintenance expenses for this type of bogies are noticeably lower compared with other types of bogies. Therefore, many engineers have focused on the structural and dynamic optimization of these bogies in order to improve their performance. Three piece bogies are currently manufactured and are in use in Iran. These bogies do not exhibit favorable curving performances in comparison with other freight bogies. There are reports of high wear rate for these bogies in curves. Various railway networks (International heavy haul association, 2001; Kalousek, 2005) throughout the world in addition to the Iranian railway have reported reduced performance for these bogies in curves. High wear rate for the outer wheel flange-gauge face region and also in the wheel tread-rail head region have been reported (International heavy haul association, 2001). Such conditions for the wheel-rail wear damage the vehicles and the rail track system. Consequently, this increases the costs of the track and rolling stock maintenance.

Also, variations in the wheel profile particularly in wheel tread results in high contact pressure that is the main source for the formation of the rail surface damage especially the rolling contact fatigue (RCF) and the rail breakage (Rezvani et al.). Moreover, variations in the wheel flange as a result of wear decreases the running safety particularly at curves (Iwnicki, 2006).

Based on the authors' observations from the maintenance depots and the internal reports from the national railway administration the axle box clearances are not appropriately respected during maintenance. This parameter can also vary while the vehicle is in service. Therefore, it is necessary to elaborate on the dynamics and curving behavior of such bogies.

Several researchers have examined the nonlinear behavior of rail vehicles. Polach (2006); Polach (2009a,b); Polach and Kaiser (2012) simulated the effects of the nonlinear wheel-rail profile on vehicle critical speed and its corresponding bifurcation diagrams. He also compared the application of the methods of path-following and brute-force for studying nonlinear rail vehicle dynamic. He proposed a method for the wheel profile design considering the critical speed, as well. In addition Shevstov (2006) studied the effects of the wheel profile on vehicle dynamic performance. He proposed some methods to choose or to design appropriate profiles, suggesting inverted method. These profiles directly correlate to the needs of the railway network. By doing so, the system can

* Corresponding author.
E-mail address: rezvani_ma@iust.ac.ir (M.A. Rezvani).

http://dx.doi.org/10.1016/j.euromechsol.2016.08.011

reach an optimized behavior in which the costs of maintenance are minimized. Wickens proposed methods in order to improve vehicle performance in straight as well as curved tracks. He also developed some methods to assess the stability, critical speed and performance of the dynamic systems (Wickens, 2006). He suggested that by designing good quality suspension systems for the bogies, vehicle curving and vehicle critical speed in addition to ride quality would improve. The problem of rolling stock bifurcation behavior and the effects of nonlinearities such as creep saturation and wheel-rail geometry were also studied by many researchers. Hoffman and colleagues investigated the dynamics and critical speed of rolling stock in curves (Petersson and Hoffman, 2002). They studied the variation of the nonlinear critical speed as function of the curve radius. Also comprehensive investigations on the critical speed of European two axle wagons were carried out by Hoffmann, (2008). Moreover, True (True, 1994, 2012; True and Thomsen, 2005; True and Jensen, 1994; Xia and True, 2003; True, 1999) studied rail vehicle bifurcation diagram behavior and chaotic motion developing nonlinear equations of motions and applying appropriate numerical methods. He also studied the problem of the existence of solutions for nonlinear equations of motion including issues on methods to find attractors such as periodic and chaotic solutions. This was in addition to the discussion on appropriate methods for examination of critical speeds. Also further exploration on the behavior of the bifurcation diagram in railway bogie systems and a discussion on solutions were performed by Gao et al., (2012). The existence of stable stationary solutions and co-existence of periodic solutions were debated, as well. The study on the performance of three piece bogie containing two dimensional friction contacts between the contacting surfaces were performed by Xia, (2002). He surveyed the behavior of a three piece bogie bifurcation diagram including the periodic-chaotic attractors with the assumption of vehicle suspension system hysteresis loop. The co-existence of chaotic and periodic attractors in bifurcation diagrams for a three piece bogie vehicle containing two dimensional friction damper elements was studied as well.

Allen and Iwnicki, (2001) conducted research on the critical speeds using roller rigs. They compared the results for nonlinear behavior of a rail vehicle on track and roller rig to understand the differences and restrictions where the vehicle becomes unstable. Additionally, further investigations on the effects of various parameters including system degrees of freedom, creep forces and suspension system properties on bogie hunting motion was performed by Cheng et al. (Minorsky, 1947; Lee and Cheng, 2005; Cheng et al., 2009). They indicated that by decreasing the system degrees of freedom, the system would exhibit higher critical speeds. A new nonlinear creep force theory was developed and its effect on the values of vehicle critical speed as a function of bogie suspension system stiffness was studied.

Despite a handful of research performed on freight bogies nonlinear dynamics in curves and straight track, less attention has been paid to the effect of some track-rolling stock parameters, which are related to operational conditions. They have an important role on the permissible velocity and freight bogie dynamic features. It is required that the permissible velocity of rail vehicles is examined according to the actual track network features. Identifying the parameters affecting the vehicle non-linear behavior and the analyses of the vehicle bifurcation diagram behavior independence on the parameter variation helps to obtain a better insight into the nature of such highly nonlinear systems.

The purpose of this research is to study the dynamic behavior of a freight wagon equipped with three piece bogies on tangent tracks and curves using a numerical method. The model is verified with field test and data reported by other researchers and Iranian railway transportation administration.

This research involves examining the effects of axle box clearances, variation in wheel-rail friction coefficient and the track curve radius on the rail vehicle nonlinear critical speed. Bifurcation diagrams and system dynamic behavior are calculated. Possibility for chaotic solutions and the effect of axle box clearances on bogie curving are also studied. Rail vehicle specifications and the track related parameters originate from real operational conditions. The effects of the axle box clearances on the wheel wear are also studied. It is to be noted that the wheel-rail contact geometry is considered as an important factor in the dynamic behavior of bogie and its bifurcation diagrams, especially in the case of curving performance. Thus the effect of wheel-rail profile geometry, and the contact point distribution for various rail inclinations on vehicle curving are surveyed. The results are discussed and recommendations are proposed to improve the vehicle dynamic performance.

1.1. Some theoretical aspects of the research

Rail vehicle hunting motion was originally treated as a linear problem. Hence, most research was performed based on linearization methods (Iwnicki, 2006; Wickens, 2006). After having solved the problem of lateral oscillations at lower running speed, further investigation proved that the hunting motion is a nonlinear phenomenon. This behavior is described as a bifurcation problem in which the rail vehicle equations of motion may have several solutions. Such solutions depend on a control parameter that is usually the vehicle running velocity. A bifurcation diagram in railway dynamics as in Fig. 1 depends on some nonlinear parameters such as the wheel rail profile and the creep forces (Polach, 2006). It was already demonstrated that the friction coefficient affects the amplitude of the wheelset lateral movement when the wheelset experiences hunting motion (Wickens, 2006). In addition it was shown that the wheel equivalent conicity will affect the bifurcation diagram (Wickens, 2006).

According to Fig. 1 with the presumption of having only periodic motion, or considering that the system only has periodic solutions, before the saddle node, if the system is laterally displaced, the lateral oscillations would die out. The system would become stable at the zero point. But after the saddle node, the system would have different stable and unstable solutions based on the initial conditions (i.e. initial lateral displacement). Then at higher speeds, the system would only have one stable solution.

According to Fig. 1, there is a certain limit speed above which, the vehicle dynamical system may change to another solution (or attractor). This speed is denoted as the critical speed (saddle node

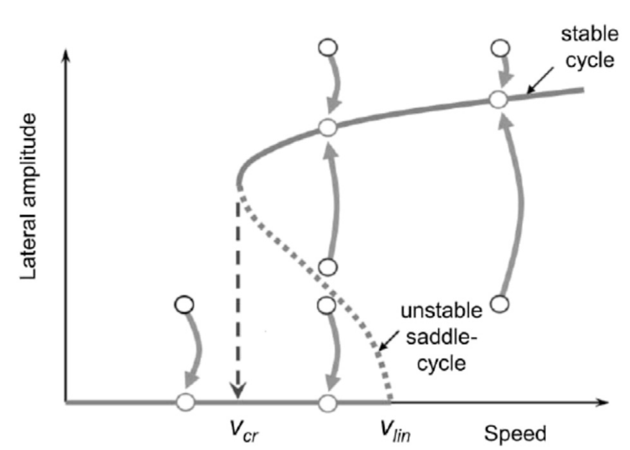

Fig. 1. Typical subcritical bifurcation diagram for the rail vehicle instability (Rezvani et al.).