On bifurcation analysis of complex railway vehicle models

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Summary. The paper deals with an application of bifurcation analysis for stability assessment of complex railway vehicle models. Two bifurcation analysis methods are presented and their performance compared: the brute-force and the path-following method. The application of the path-following method is restrained because of quasi-periodic motions occurring at complex models due to coupling of bogies through the car body, while the brute-force method delivers the bifurcation diagram independently on model complexity and of the type of the solution.

Introduction

The stability assessment of railway vehicles is one of the most important tasks of dynamic analysis in railway vehicle engineering. Comprehensive railway vehicle stability investigations based on linearized models during 1960/70 have been enhanced considering the non-linearities of the wheel/rail contact and other elements of the system vehicle/track at a later date. Moelle and Gasch [1] and True et al. [2, 3] can be mentioned if only in a representative manner. True and his co-workers investigated various aspects of non-linear railway vehicle stability analysis under application of the continuation-based bifurcation analysis (path-following method) developed by Kaas-Petersen [4]. Schupp [5] integrated this path-following method into the multi-body simulation tool Simpack. From many other papers related to bifurcation of railway vehicles we can mention the works by Stichel [6], Molatefi et al. [7] and Hoffmann [8], who investigated the stability of freight wagons on straight tracks, and stability analyses on curves by Zboinski and Dusza [9].
The publications dealing with non-linear stability assessment of railway vehicles often investigate simplified models, conical or theoretical wheel profiles and theoretical rail profiles. Considering a complex multi-body vehicle/track model including variations of wheel/rail contact geometries and friction conditions in railway service, the actual behaviour of a railway vehicle at the stability limit can vary significantly depending on the non-linear properties of the actual wheel/rail contact conditions as presented by one of the authors in [10].
The stability assessment in railway rolling stock industry requires the possibility to apply the stability analysis on complex vehicle models under realistic conditions of operation. This results to a large number of computations considering various wheel/rail conditions [11, 12]. The present paper deals with an application of bifurcation analysis for the stability assessment of a complex railway vehicle model used in the rolling stock industry. Two methods of bifurcation analysis are presented and their performance compared.

Bifurcation analysis by path-following and brute-force method

When analysing the stability of railway vehicles, the bifurcation diagram displays the amplitude of the limit cycle (typically lateral wheelset displacement) as a function of vehicle's running speed. The calculation of the bifurcation diagram can proceed by a set of numerical simulations or by the path-following method [4]. Whereas the path-following method has been used mostly with rather limited models and with non-commercial simulation computer codes, the rather straight forward method using a set of numerical simulations (brute-force method) is applicable in any multi-body simulation code including commercial tools. The procedure can be a ramping [2] (reducing the speed in small steps, starting from a limit cycle at a high speed) or a series of simulations for different speed steps. In the second method, the limit cycle oscillations occur as a result of initial conditions or lateral excitation in the initial section of track and the simulation continues on an ideal track. In both variants, it has to be checked for each result, whether all transient processes have died out and the attractor is reached. Varying the initial conditions or the lateral disturbances for each speed step, the bifurcation point and also the unstable branch can be identified [12].
The path-following routine developed by Schupp [5] was applied on a model of a double-decker coach with 2 two-axle bogies developed in the rolling stock industry and used previously for bifurcation stability analysis by the brute-force method [12]. This three-dimensional, non-linear vehicle model in Simpack possesses 72 degrees of freedom. In addition to the non-linear wheel/rail contact properties, the model includes non-linearities in suspension elements and also a pendulum effect of the anti-roll device with inclined vertical bars. The bifurcation analyses have been carried out for several variants of wheel/rail contact geometries and friction coefficient values.
The investigation has shown that the path-following method can be applied even to complex multi-body railway vehicle models. However, there are some restrictions. Since the path-following method exploits the periodicity of the motions for the direct calculation, the case of quasi-periodic motions cannot be handled. It has turned out that even for a vehicle with two bogies a quasi-periodic behaviour occurs in wide ranges of running speeds. These quasi-periodic oscillations can be explained by coupling of the bogies' motion through the car body. The motion of the system is governed by the self-excited bogie motion as well as by its interaction with the other components of this system. A periodic solution

exists if the motions of both bogies are synchronised; otherwise a quasi-periodic solution occurs. The periodic motion takes benefit from stronger coupling between bogies and car body (e.g. stiffer lateral or yaw car body suspension, higher lateral or yaw damping) or from weaker self- excitation of bogies (e.g. low wheel/rail friction coefficient), respectively.

The brute-force method allows the bifurcation analysis and yields the non-linear critical speed independently of the type of limit cycle motion. A comparison of the brute-force method and the path-following method is exemplarily shown in Fig. 1. This figure displays the limit cycle amplitude of the second wheelset, which showed in both methods the periodic solution at lower speed than other wheelsets. In spite of some deviations due to lower exactness of the brute-force method, the agreement in the range of speeds with periodic solutions can be stated as sufficient for engineering applications. The attractors are not complete using the path-following method because of the missing quasi-periodic solutions which cannot be handled by the direct calculation. The comparison demonstrates that the use of the brute-force method is sufficient for the needs of railway engineering, in spite that it is less exact than the path-following method and some of attractors close to each other can be overseen occasionally.

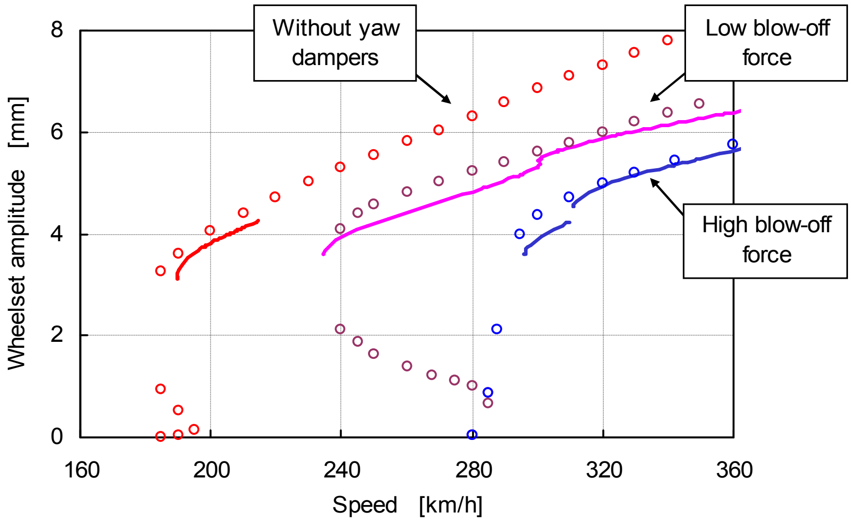

Figure 1. Bifurcation diagrams of a double-decker passenger coach with and without yaw dampers. Comparison of results calculated by brute-force method (circles) and path-following method (solid lines).

Conclusions

The presented comparison of brute-force and path-following methods for bifurcation analysis demonstrates that the application of the path-following method on complex multi-body models of railway vehicles is possible. However, since the path-following method exploits the periodicity of the motions for the direct calculation, the case of quasi-periodic motions cannot be handled. Such quasi-periodic solutions have appeared at a conventional vehicle with two bogies due to interaction between the self-excited bogie motions via the car body. Even wider ranges of speeds with quasi-periodic solutions can be expected at models of more complex vehicles, which would restrain the application of this method on such complex models. The brute-force method provides the shape of bifurcation diagram, although with lesser accuracy, independently of vehicle model complexity and fulfils the needs of railway engineering.

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