VPS VIBRATIONS IN PHYSICAL SYSTEMS

DOI: 10.21008/j.0860-6897.2024.1.19
Vibrations in Physical Systems, 2024, 35(1), 2024119

Impact of specific geometric parameters of the axle on the modal characteristics of vibration

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Abstract This scientific article presents a comprehensive examination of vibration frequency characteristics pertaining to wheelset axles, crucial components in railway systems. By exploring the significance of vibration frequency research in railway engineering, we aim to contribute valuable insights into the operational integrity and safety of railway vehicles. Building upon existing studies, our investigation delves into specific parameters related to axle vibration frequencies. With potential applications in axle and wheelset design, our research seeks to advance the efficiency and safety of modern railway transportation systems.

Keywords: wheelset axles, rail vehicles, FEM calculations, vibration frequencies.

1. Introduction

In the ever-advancing world of transportation, the efficient and reliable functioning of railway systems remains paramount. One crucial aspect that directly influences the performance and safety of railway vehicles is the behavior of their axles and wheelsets. Vibration frequencies play a significant role in assessing the health and operational integrity of these components. The present scientific article delves into a comprehensive investigation of vibration frequencies associated with axles of wheelsets, aiming to contribute valuable insights to the realm of railway engineering.

The scientific literature refers to vibration as the mechanical oscillations of bodies around their equilibrium positions. This phenomenon occurs in many fields of engineering and physics, from building structures to mechanical systems. Vibration studies play a key role in designing, diagnosing, and optimizing various systems. In medicine, where precision is of utmost importance, the impact of vibration is also a crucial consideration. The article [1] presents an analysis of natural frequencies and shapes of vibration of the arm and working end of the da Vinci robot. The results presented in the cited paper are of paramount importance to prevent resonance. Research highlighted in [2] focuses on establishing criteria for designing protective guards, particularly against the damaging effects of small, sharp components. These guards serve a dual purpose: mitigating the influence of foreign objects on protective covers and minimizing the impact of external noise and vibration on the vehicle's interior. J.Y. Shih, D.J. Thompson, and A. Zervos explored the impact of nonlinear ground properties on track vibration resulting from trains' movement on soft ground [3]. This investigation sheds light on the intricate interplay between ground characteristics and track vibration. Meanwhile, [4] delves into the repercussions of train-induced vibration on both the track structure and the surrounding environment. This article also delves into the evolution of vibration reduction efficiency over extended operational periods. In another article [5], an intriguing experimental field study unfolds, detailing vibration and noise phenomena. Notably, the connection between self-excited vibration, back vibration of corrugated irregularities, and wheel-rail friction's influence on rail corrugations is explored in [6]. This research significantly contributes to our understanding of complex vibration patterns and their underlying factors. On the other hand, the influence of the state of dry and wet road surface on the dynamic reactions of the types of surgical procedures. However, within the context of railway infrastructure, axle vibration holds the potential to induce fatigue, structural deformation, and vibration perceptible to passengers. In the case of axle vibration, the oscillations of other connected components are also vehicle was described in [7]. The work [8] focused on the influence of the vibration amplitude and axle load on the rolling contact of the rail. The tests showed that the degree of crack damage increased with the increase of both the axle load and the vibration amplitude. Collectively, these studies represent a

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multifaceted exploration of vibration, ranging from robotics and transportation to environmental impact, encompassing practical implications and theoretical insights.

In the forthcoming article, our focus will be directed towards an advanced approach for analyzing the vibration of railway axles: finite element method (FEM) simulation. This technique facilitates precise modeling of the dynamic behavior of intricate structures. When coupled with the analysis of natural frequencies of vibration, it provides insights into the inherent vibration form and dynamic characteristics of the axles under examination.

Natural frequencies of railway axles depend on many factors, such as their dimensions, shape, mass and material properties. In the course of our research, we will focus on the analysis of various combinations of dimensions and masses of railway axles, based on article [9], to understand how these variables affect their dynamic behavior. Utilizing advanced computer simulation tools, we will be capable of subjecting the axles under examination to a range of loading conditions and dynamic interactions in a virtual environment. Nonetheless, this aspect was also explored in a different discipline, as discussed in the article [10]. In this instance, the study focused on vibration induced by fluid flow in plates with varying Poisson's ratios.

As a result of this study, we anticipate deriving valuable insights concerning the natural frequency of railway axles based on their parameters. This, in turn, will contribute to a deeper comprehension of the dynamic characteristics of the axles and facilitate potential design optimizations aimed at enhancing the efficiency and safety of the railway system.

2. Research object

The study of vibration frequency in railway axle systems holds immense significance in the domain of railway engineering, as it directly influences the mechanical stability, performance, and safety of railway vehicles. To gain comprehensive insights into the dynamic behavior of these critical components, engineers and researchers have increasingly turned to advanced numerical techniques, such as the Finite Element Method (FEM). In this chapter, the results of tests carried out using FEM will be presented with the objective of uncovering crucial resonance characteristics and providing a deeper understanding of the dynamic response of axles with different geometry.

The axis was adopted for the tests on the basis of the data contained in [9]. The tested variants are shown in Figure 1 and Table 1.

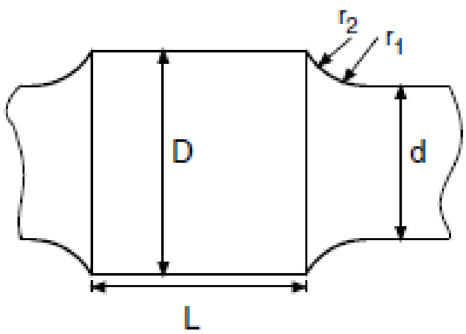

Figure 1. Test rigs and testpiece geometry detailed shape of the press-fitted part [9].

Table 1. Axle geometry at press-fit [9].

	D [mm]	d [mm]	D/d [mm]	r_1 [mm]	r_2 [mm]	l [mm]
F1-Vitry	190	160	1.19	75	15	185
F4-Vitry	165	147	1.12	75	15	185
F4-Minden	165	147	1.12	75	15	190

3. FEM simulation analysis

The Finite Element Method (FEM) is a powerful numerical technique widely employed in engineering and applied sciences for solving complex mathematical problems and analyzing the behavior of structures and systems. This method discretizes a continuous domain into smaller, manageable elements, allowing for the approximation of solutions to partial differential equations. The use of FEM also allows for significant savings by eliminating many bench tests. Thanks to it, it is also possible to properly prepare the model for experimental research by determining the appropriate measurement parameters or indicating the most favorable location of strain gauges.

The strength analysis was performed with the SolidWorks 2022/23 program with the Simulation module based on the Finite Element Method. The tests of the natural frequency of vibration were performed on the computational model shown in Fig. 2a. The material used is EA1N steel with Young's modulus E = 210 GPa and Poisson's number ν = 0.26.

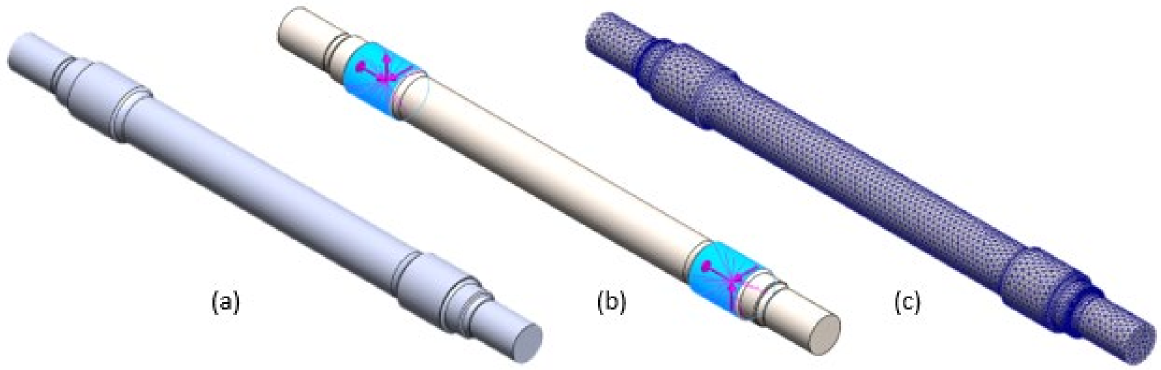

Figure 2. View of the tested axis: (a) calculation model, (b) boundary conditions, (c) division into finite elements.

Support conditions were introduced to the computational model (see fig. 2b). Boundary conditions are applied to the surfaces marked with the blue color. On the left, translations in three perpendicular directions and rotation around the shaft axis were blocked, while on the right, translations perpendicular to the axis and rotation around the shaft axis were blocked. The above restraints allow the symmetry to be maintained despite blocking the axial translation on the left side, while not excluding asymmetric forms of vibration. The model was not loaded for the study of natural vibration.

When employing a numerical approach to tackle a mathematical conundrum, a crucial preliminary step involves discretizing the problem by partitioning the boundary of a designated region, as depicted in Figure 2c. Through this process, the complex problem is transformed into a set of manageable components, facilitating computational analysis. In the case at hand, the model was meticulously divided into finite elements, ultimately resulting in the assembly of 111 594 nodes and 74 614 elements. This configuration was established utilizing a tetrahedral solid mesh constructed from second-order finite elements, a robust foundation for accurate computations. Following the construction of the mesh, a meticulous assessment of its quality and the arrangement of elements along measurement lines was conducted. The paramount objective was to eliminate the presence of deformed elements, which could compromise the reliability of subsequent analyses. Subsequent to this thorough examination, a strategic decision was made to enhance the mesh's precision around curved sections, warranting a refined mesh configuration. Consequently, the maximum dimension of individual mesh elements was set at 20 mm, ensuring precision in complex regions, while the minimum size was defined at 1mm, preserving detail in more straightforward areas.

4. Results

Upon completion of the computer simulation, a comprehensive set of natural angular frequencies ω and natural frequency f results emerged for the cases under consideration, meticulously detailed in tables 2 to 4. These tables provide an organized presentation of the distinct natural frequencies corresponding to the different scenarios explored in the study. Meanwhile, the intricate and nuanced forms of vibration that emerged from these simulations are vividly illustrated through Figures 3 to 5. These visual representations offer a tangible glimpse into the complex vibrational patterns that were identified, enabling a more intuitive understanding of the diverse dynamics at play within the analyzed systems.

Table 2. F1-Vitry axis vibration modes.

Vibration mode	ω [rad/s]	f [Hz]	t [s]
1	925.6	147.31	0.0068
2	927.16	147.56	0.0068
3	2884.6	459.1	0.0022
4	2890.4	460.02	0.0022
5	4707.7	749.25	0.0013

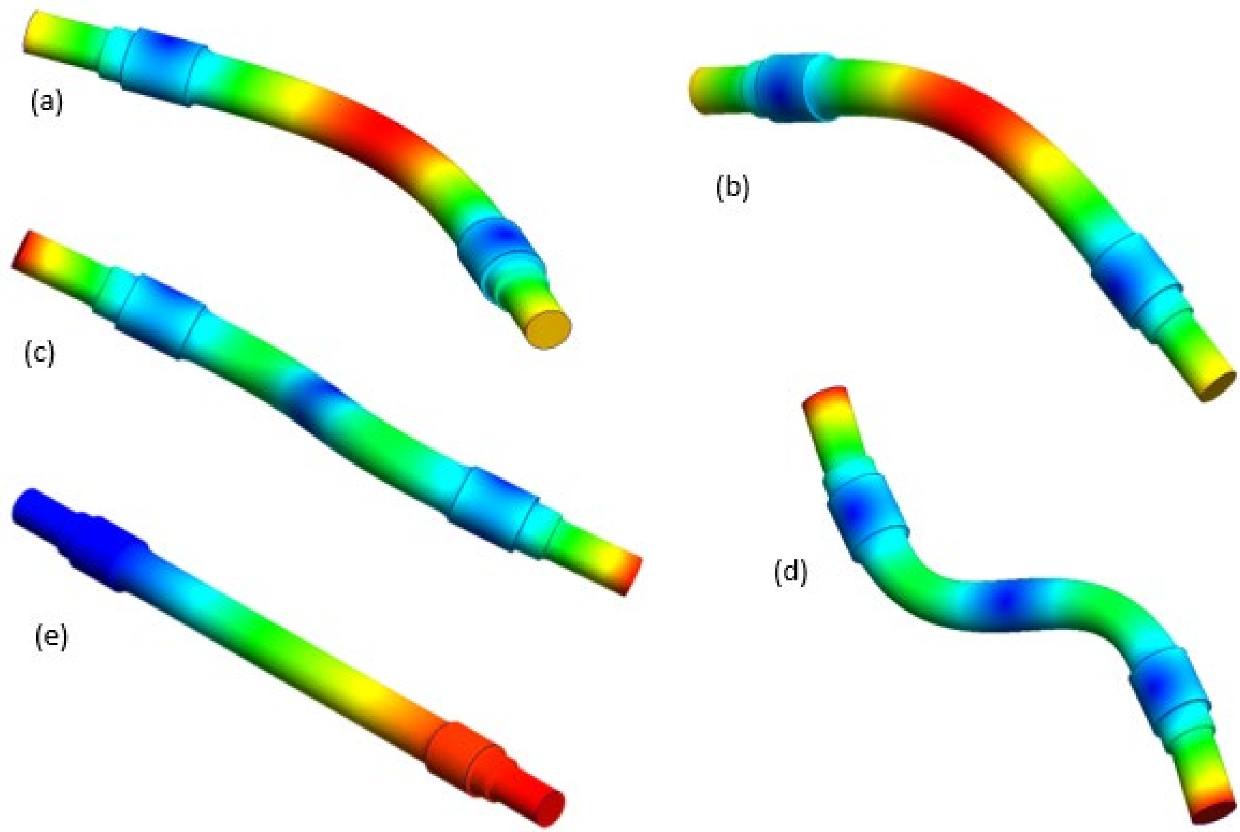

Figure 3. F1-Vitry eigenfrequency modes:
(a) first and (b) second modes, transverse vibration (shown in two perpendicular planes),
(c) third and (d) fourth forms, transverse vibration (shown in two perpendicular planes),
(e) fifth form, longitudinal vibration.

Figure 3a and 3b present the first vibration mode in two perpendicular planes. The calculated forms are the same but in two planes, which results from the FEM used. The obtained frequencies differ, but the difference do not exceed 0.22%. Under ideal conditions, with symmetry in geometry and boundary conditions, these results would align. However, the mesh structure of tetrahedrons disrupts this symmetry, leading to numerical differences in frequencies. Similarly, in Figures 3c and 3d, the second mode of vibration is depicted, with negligible differences observed between the results.

Table 3. F4-Vitry axis vibration mode.

Vibration mode	ω [rad/s]	f [Hz]	t [s]
1	844.12	134.35	0.0074
2	845.22	134.52	0.0074
3	2588.3	411.94	0.0024
4	2589.0	412.05	0.0024
5	4391.1	698.86	0.0014

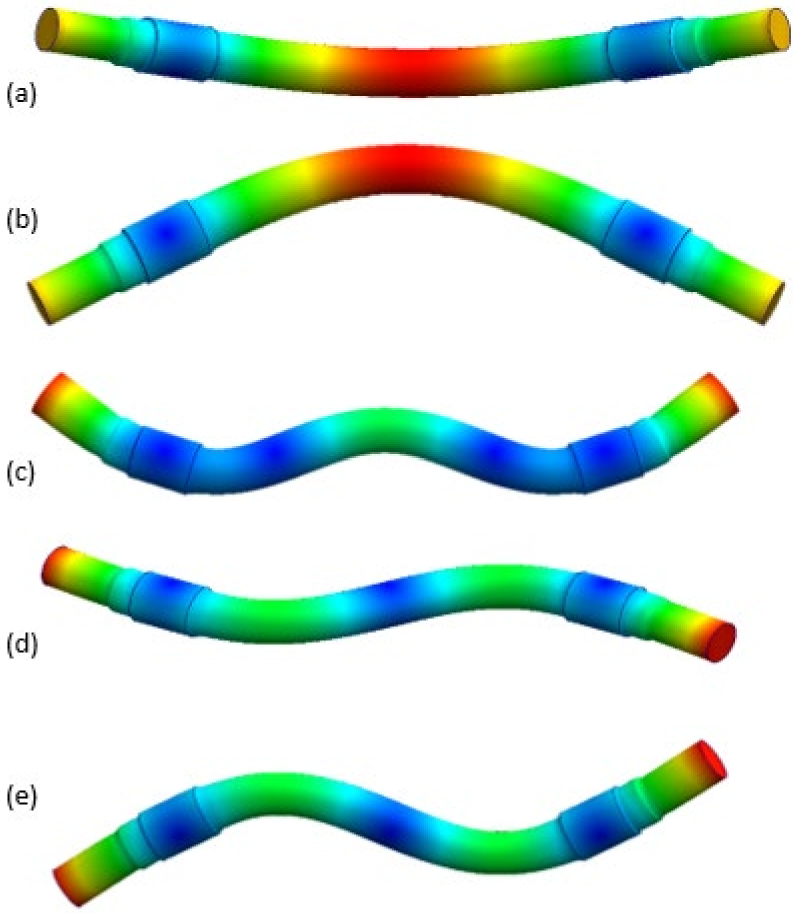

Figure 4. F4-Vitry eigenfrequency forms:
(a) first and (b) second modes, transverse vibration (shown in two perpendicular planes),
(c) third and (d) fourth forms, transverse vibration (shown in two perpendicular planes),
(e) fifth form, transverse vibration.

A similar situation as for the first axis also occurs for the second axis. The calculated difference for first and the second modes do not exceed 1.3%. Figures 4a and 4b showcase the first mode, while Figures 4c and 4d illustrate the second mode.

Table 4. F4-Minden axis vibration mode.

Vibration mode	ω [rad/s]	f [Hz]	t [s]
1	850.6	135.38	0.0074
2	851.0	135.44	0.0074
3	2592.8	412.66	0.0024
4	2593.5	412.78	0.0024
5	4411.5	702.11	0.0014

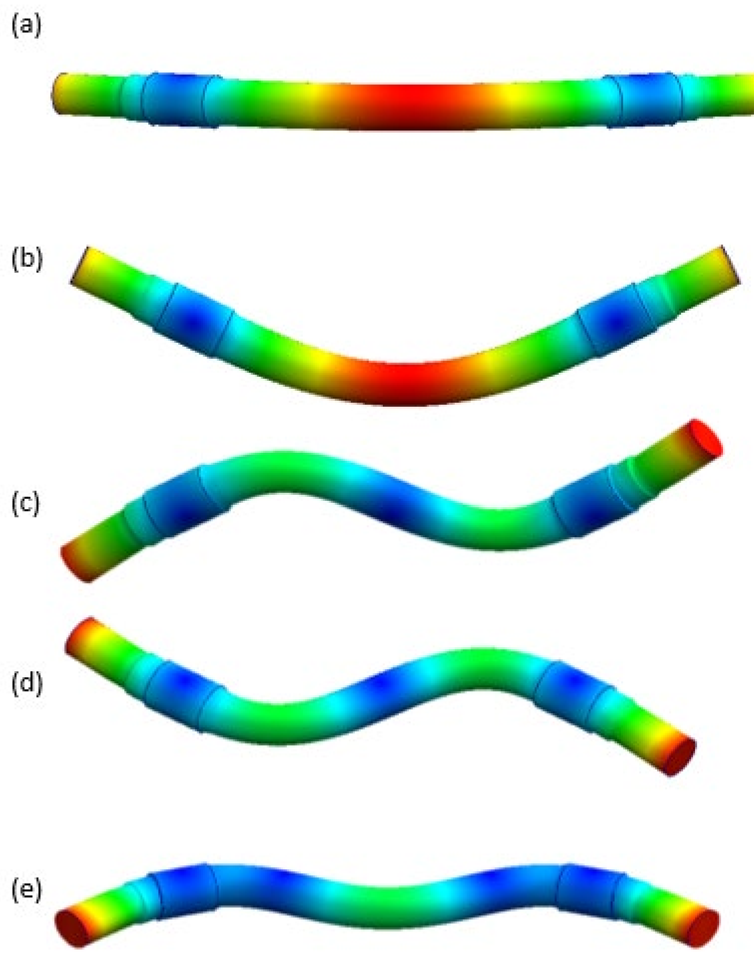

Figure 5. F4-Minden eigenfrequency forms:
(a) first and (b) second modes, transverse vibration (shown in two perpendicular planes),
(c) third and (d) fourth forms, transverse vibration (shown in two perpendicular planes),
(e) fifth form, transverse vibration.

The results for the third axis differ by up to 0.05% between the first and second modes. The first mode is presented in Figure 5a and 5b, while the second mode is shown in Figure 5c and 5d.

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4. Conclusions

Based on the conducted research, we can conclude that the F1-Vitry, exhibits resonance frequencies that are significantly different from both versions of the F4 axles. The observed discrepancies in resonance frequencies between F1-Vitry and F4 axles suggest distinct dynamic characteristics and mechanical properties in these axle variants.

Research also shows that the F1-Vitry axle demonstrates higher vibration frequencies for individual forms (modes of vibration) compared to both versions of F4 axles. The higher vibration frequencies in F1-Vitry indicate a more rapid and energetic response to external stimuli compared to the F4 axles.

Additionally, it can be seen from the data that there are no significant differences between the two versions of F4 axles concerning vibration forms and frequencies. The lack of substantial variation is attributed to a small difference in just one of the dimensions, specifically the length (l) of the axles. This suggests that the dimensional similarity of F4 versions results in comparable vibration behavior.

A fundamental disparity in vibration behavior is discernible between F1 and F4 axles. In F1 axles, vibration in the fifth form are longitudinal vibration. In contrast, for F4 axles, these vibration are lateral. This dissimilarity is influenced by the larger diameter of the F1 axle, which contributes to distinct vibrational patterns.

The underlying factors driving fluctuations in vibration frequencies become readily apparent upon closer examination. The pivotal catalyst behind these variations is primarily the alterations in the shaft diameters of the axles. This seemingly subtle parameter wields a profound influence, as it significantly impacts two critical aspects: the mechanical stiffness and the distribution of mass within the axle structure. This intricate interplay becomes the linchpin of the axle's natural frequencies of vibration. The mechanical stiffness, intrinsically tied to the shaft diameter, acts as a governing force dictating the axle's responsiveness to external forces and its inherent tendency to oscillate. Simultaneously, the distribution of mass, intricately linked with the same shaft diameter, forges the axle's characteristic vibrational patterns. As the mass distribution shifts with changes in diameter, the resultant vibration manifest at distinct frequencies. Therefore, the discernible variations in vibration frequencies among different axle variants can be confidently ascribed to the variations in their corresponding shaft diameters. This crucial parameter emerges as the dominant factor, orchestrating the dynamic relationship between mechanical stiffness, mass distribution, and natural frequencies of vibration.

The vibration of the wheelsets influence the undulating wear of the railway tracks. The primary mode of natural vibration for rail bogie frames oscillates around 1-1.5 Hz. Delving deeper into the intricacies of bogie frame vibration, their upper frequency threshold emerges as a significant parameter. This upper range, varying between 7 to 10 Hz, hinges upon the distinct suspension attributes and mass properties of bogie frames. The interplay between these factors yields variations in the upper limits of vibration frequencies. A compelling outcome of this analysis is the realization that the likelihood of coupling between axle and bogie frame vibration is effectively negligible.

These conclusions provide valuable insights into the vibration characteristics of different axle variants and offer essential knowledge for designing and optimizing axles in railway systems, ultimately contributing to enhanced performance, safety, and efficiency of railway vehicles. By comprehending and manipulating the relationship between axle geometry and vibration, engineers and researchers gain a profound insight into the intricate mechanics of axles and their vibrational behavior, a vantage point essential for shaping optimal axle designs and refining railway systems' performance.

Acknowledgments

The research was carried out as part of the Implementation Doctorate Program of the Ministry of Education and Science implemented in the years 2021-2025 (Contract no DWD/5/0378/2021).

Additional information

The author(s) declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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