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Effect of Aging of Bearings on the Behavior of Single-Span Railway Bridges

Emrah Erduran(✉), Christian Nordli, Mohammadreza Salehi, and Semih Gonen

Oslo Metropolitan University, 0166 Oslo, Norway
emrah.erduran@oslomet.no

Abstract. Elastomeric bearings are ubiquitous in railway bridges as they provide flexibility that prevents stress concentrations near the supports due to temperature-related material contraction and expansion. Their inherent flexibility affects the overall stiffness and the vibration frequencies of the bridges. Furthermore, the stiffness of the bearings can vary significantly during the lifetime of the bridge due to several factors such as material deterioration and aging and can directly impact the behavior of the bridge. This article investigates the impact of the variations in the stiffness of elastic bearings on the train-induced vibrations on single-span railway bridges. A series of parametric analysis for different train speeds was conducted. The analysis were repeated for a wide-range of bearing stiffness that represents the variation of this parameter during the lifetime of the bridge. The results indicate that, the variations in the bearing stiffness due to aging and deterioration have significant impact on the train-induced vibrations.

Keywords: Aging · Bearings · Railway bridge · Train-bridge interaction · Dynamic response · Resonance · Cancellation

1 Introduction

Elastomeric bearings are ubiquitous in railway bridges as they provide flexibility that prevents stress concentrations near the supports due to temperature-related material contraction and expansion. Furthermore, variations of bearings are widely used in seismic regions to protect the bridges from damaging effects of severe earthquakes. While they are effective in protecting the bridge superstructure, they may significantly impact the modal properties of the bridge and, as such, the dynamic behavior of the bridge under moving train loads at different speeds. Furthermore, the characteristics of the bearings are prone to significant variations during the lifetime of a bridge [2].

If the dynamic response of the bridge under moving train loads is sensitive to the bearing characteristics, deviations of these characteristics from the assumed values during the design phase may significantly alter the dynamic response

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of the bridge during its lifetime. Despite this potentially significant impact, few studies have focused on the interaction between the bearing stiffness and dynamic response. Arguably, Choi and Kim [1] and Yang et al. [3] present the most detailed work on the subject. Similar studies were also reported in [4–6].

This article systematically investigates the effects of variations in the stiffness of the elastomeric bearings on the dynamic behavior of railway bridges under moving train loads. For this, numeric model of a 50 m long railway bridge is created. Dynamic analysis of the bridge under a heavy-haul train was conducted for varying bearing stiffness and the variation of the response parameters with this parameter was studied. The key factors affecting the dynamic response of the bridge is investigated and the potential impacts of the variations in the bearing stiffness on the dynamic response is evaluated.

2 Numerical Model and Analysis

The railway bridge used in the analysis is a single-span, 50 m long prestressed concrete bridge. Modulus of elasticity of concrete was assumed to be 32 GPa and the moment of inertia of the cross-section about the main bending axis is 16.89 m^4. The total mass of the bridge was computed as 22.9 t/m including the non-structural elements such as the track bed and ballast, which was assumed to be 30% of the self-weight of the concrete deck. The bridge is discretized at each meter and the mass of each element is lumped at the nodes. The horizontal movement in the supports is restrained while the ends of the bridge are free to rotate. The vertical stiffness of the bearings are modeled using elastic springs with a stiffness of k_v. In this article, the vertical bearing stiffness k_v was varied between 1×10^3 kN/m and 1×10^{15} kN/m to investigate the effect of this parameter on the dynamic behavior of the bridge. Figure 1 presents the overview of the numerical model of the bridge.

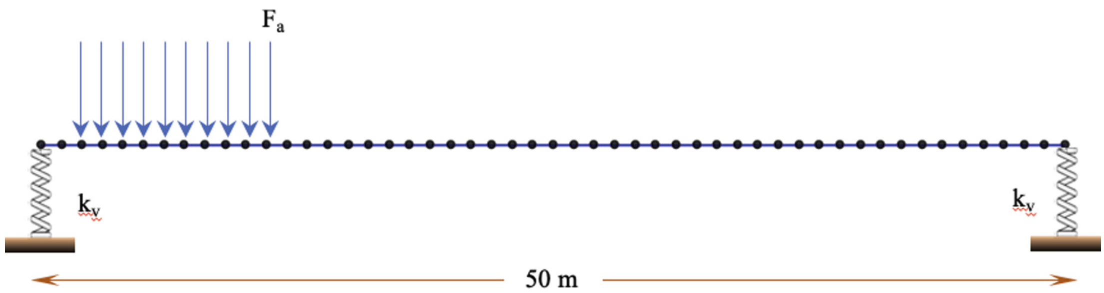


Fig. 1. Overview of the numerical model

Eigen-value analysis were conducted on the bridge for varying bearing stiffness values to explore the impact of this parameter on the modal parameters of the bridge. Figure 2 shows the variation of the modal frequencies of the first three modes of the bridge with the bearing stiffness. It can be deducted from

Fig. 2 that the behavior of the bridge does not vary significantly once the vertical stiffness exceeds 1×10^8 kN/m as the frequencies of the first three modes remain the same once this threshold is reached. Furthermore, the difference between the modal frequencies between the cases when $k_v = 1 \times 10^7$ kN/m and $k_v = 1 \times 10^8$ kN/m are very subtle, particularly for the first two modes. Once k_v value reduced below 1×10^7 kN/m, the modal frequencies start to change drastically.

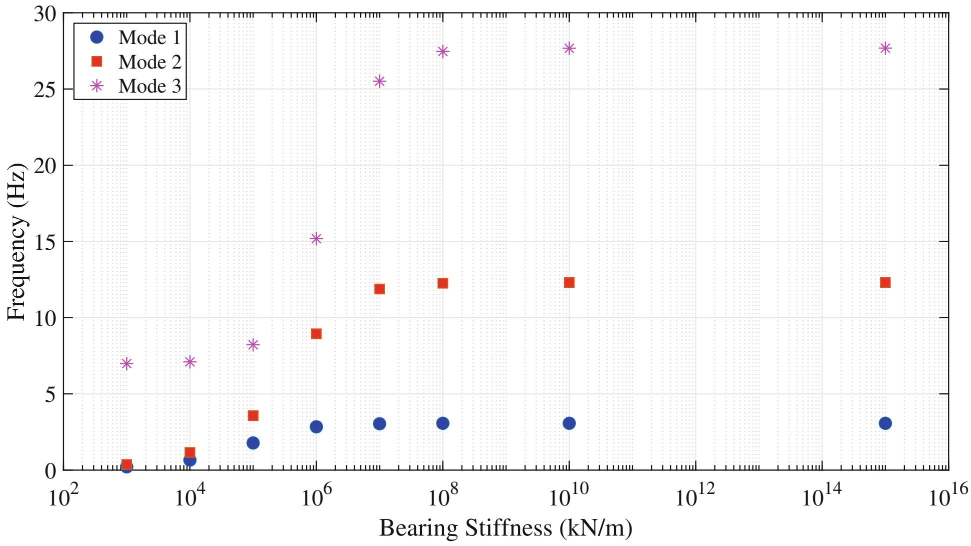


Fig. 2. Variation of the bridge natural frequencies with the bearing stiffness

As the next step, elastic moving load analysis was carried out to investigate the impact of the bearing stiffness on the behavior of the bridge under train loading. The train loads are modeled as a set of moving loads as illustrated in Fig. 1 each load representing the axle load of the train, F_a. In this article, a heavy-haul train with a total number of axles of 268 and an axle load of $F_a = 300$ kN was used

Figure 3 depicts the maximum accelerations computed at the middle of the bridge span under moving train loads traveling with speeds of 50, 80, 120, and 200 km/h. The impact of the bearing stiffness on the acceleration response of the bridge for each train speed is clear from the figure. The maximum accelerations increase significantly once the vertical bearing stiffness, k_v, drops below the threshold value of $k_v = 1 \times 10^8$ kN/m and continues the increase with decreasing k_v values. For $k_v \geqslant 1 \times 10^8$ kN/m, the acceleration values remain virtually constant as the bearing behaviour becomes infinitely stiff at this threshold value.

An interesting observation from Fig. 3 is that the maximum acceleration demand increases significantly when the bearing stiffness is decreased from $k_v = 1 \times 10^{10}$ kN/m to $k_v = 1 \times 10^7$ kN/m. Although this is in line with the general trend of increased accelerations with decreasing bearing stiffness, a quick look at Fig. 2 reveals that the frequencies of the first three vertical modes of the bridge remain virtually identical for these bearing two stiffnesses.

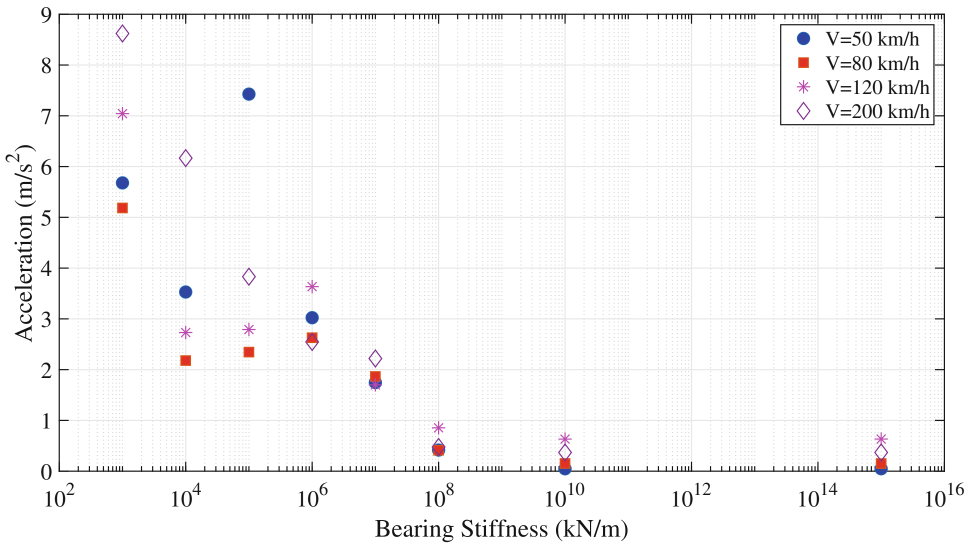


Fig. 3. Variation of the maximum acceleration at the mid-span with the bearing stiffness

The acceleration time histories at the mid-span plotted in Fig. 4 show the dramatic change in the acceleration response of the bridge thoroughout the entire loading when the bearing stiffness is reduced from $k_v = 1 \times 10^{10}$ kN/m to $k_v = 1 \times 10^7$ kN/m.

To understand the reason behind this significant variation in acceleration demands despite the modal frequencies being virtually equal, the first and third mode shapes for $k_v = 1 \times 10^7$ kN/m and $k_v = 1 \times 10^{10}$ kN/m are plotted in Fig. 5. While the first mode shape remains identical for the two cases, there is a significant difference in the third mode shape, particularly at the bearing locations for $k_v = 1 \times 10^{10}$ kN/m and $k_v = 1 \times 10^7$ kN/m. A closer look at Fig. 2 also shows that, while the first two modal frequencies remain the same when the bearing stiffness is reduced from $k_v = 1 \times 10^{10}$ kN/m to $k_v = 1 \times 10^7$ kN/m, the third modal frequency is reduced from 27.67 Hz for $k_v = 1 \times 10^{10}$ kN/m to 25.11 Hz for $k_v = 1 \times 10^7$ kN/m.

As the next step, Fast Fourier Transformation (FFT) was applied to the acceleration time histories depicted in Fig. 4 and the resulting Fourier Amplitude Spectrum (FAS) is plotted in Fig. 6. The FAS depicts a striking a difference in the dynamic behavior of the bridge when the vertical bearing stiffness was reduced from $k_v = 1 \times 10^{10}$ kN/m to $k_v = 1 \times 10^7$ kN/m. For the former case, the predominant frequency is around 3 Hz indicating that the dynamic behavior is dominated by the first vibration mode of the bridge. On the other hand, for a bearing stiffness of $k_v = 1 \times 10^7$ kN/m, the dominant frequency shifts from the first mode frequency to the third mode frequency with the energy at a frequency of 24.5 Hz being much larger than that compared to the lower frequencies. In other words, although the change in the modal frequencies due to the variation in the vertical bearing stiffness is subtle, it is significant enough to change the mode that dominates the dynamic behavior.

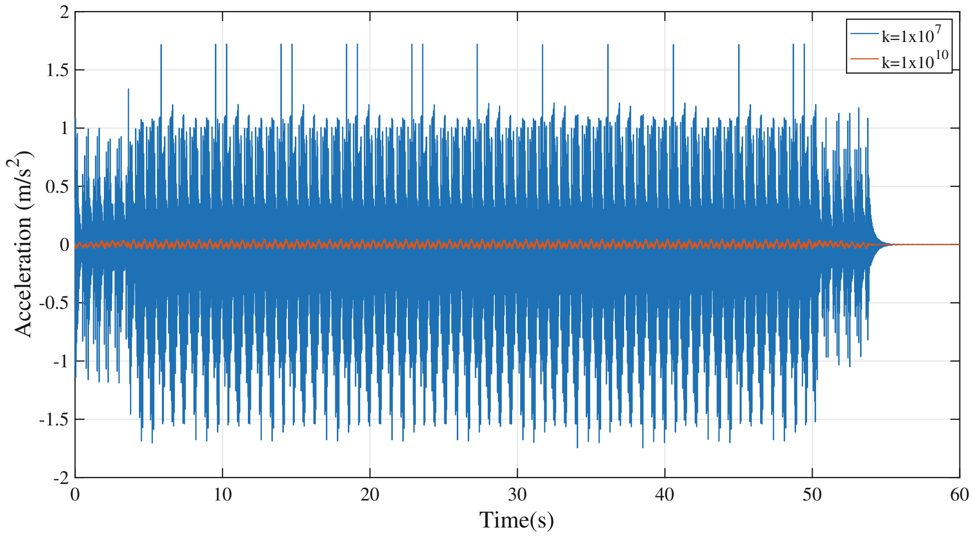


Fig. 4. Acceleration time history of the mid-span for different bearing stiffnesses for a train speed of 50 km/h

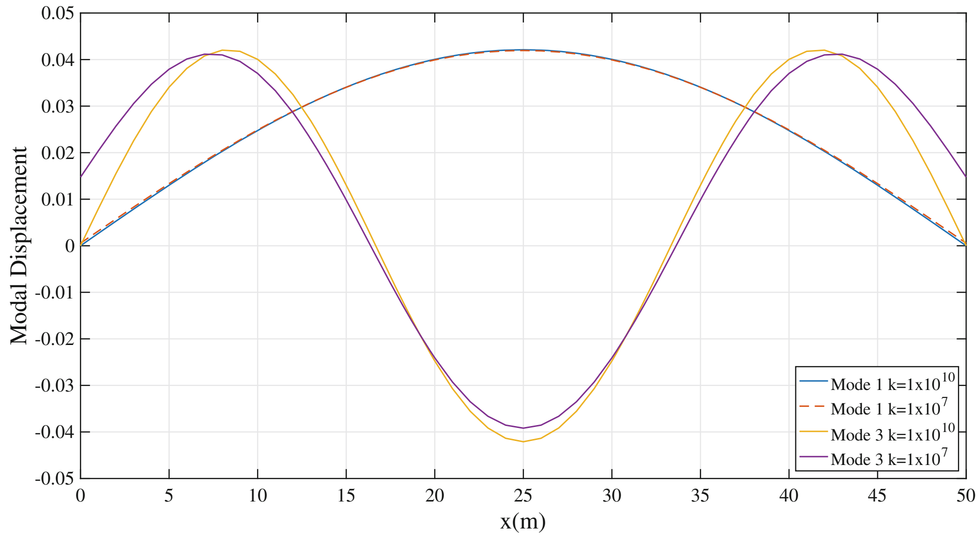


Fig. 5. Mode shapes of the bridge with different bearing stiffnesses

Finally, the Fourier Amplitude Spectrum of the train loading for a train speed of V = 50 km/h is depicted in Fig. 7. Figure 7 shows that, as the frequency of the third mode of the bridge is reduced from 27.67 Hz to 25.11 Hz, it comes very close to the loading frequency of 24.5 Hz (Fig. 7). As such, the third mode of the bridge with vertical bearing stiffness of $k_v = 1 \times 10^7$ kN/m goes into resonance with the loading frequency leading to the very high energy content at $f = 24.5$ Hz (Fig. 6) and, consequently, the higher acceleration demands in the mid-span.

To evaluate the effect of the bearing stiffness on the frequency content of the accelerations, Fourier Amplitude Spectrum of the mid-span accelerations for different spring stiffnesses is plotted in Fig. 8. Figure 8a depicts the cases where

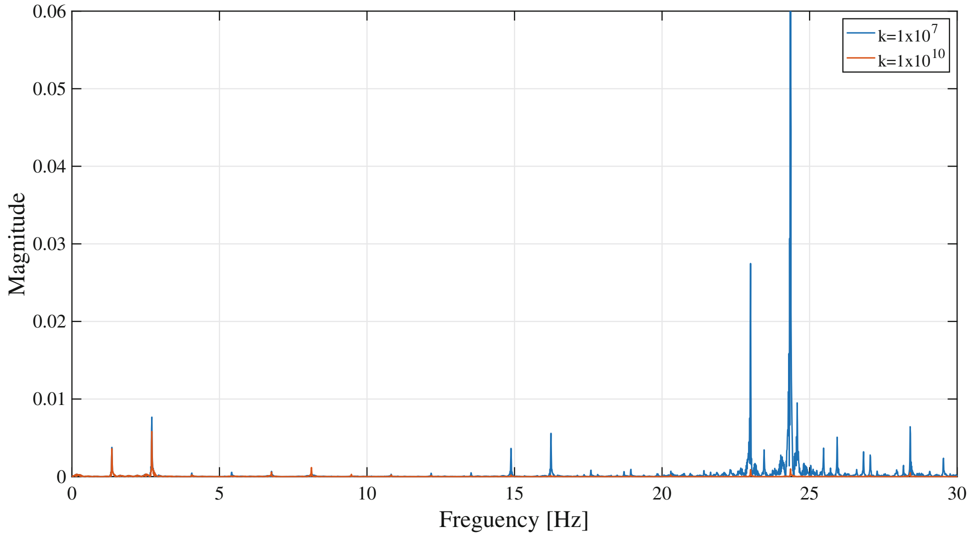


Fig. 6. Fourier Amplitude Spectrum of the acceleration time history for $k_v = 1 \times 10^7$ kN/m and $k_v = 1 \times 10^{10}$ kN/m for a train speed of 50 km/h

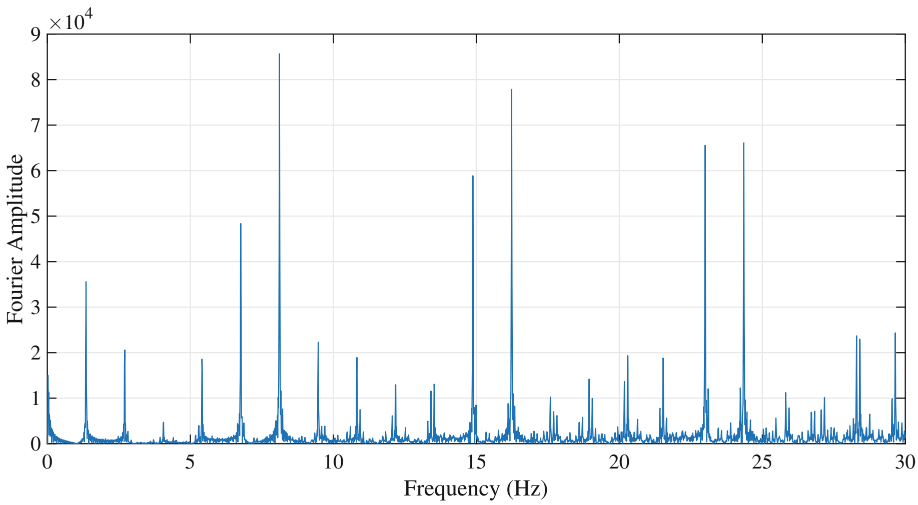
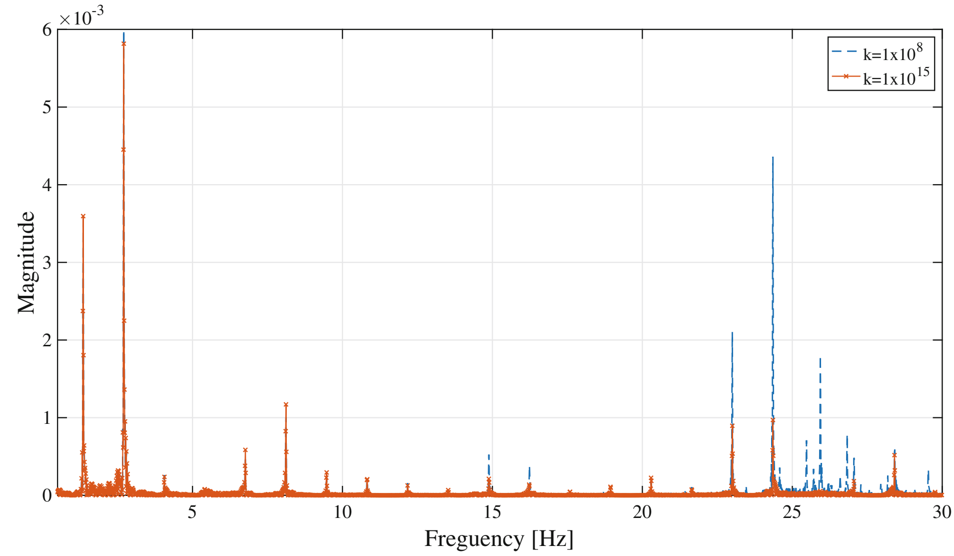
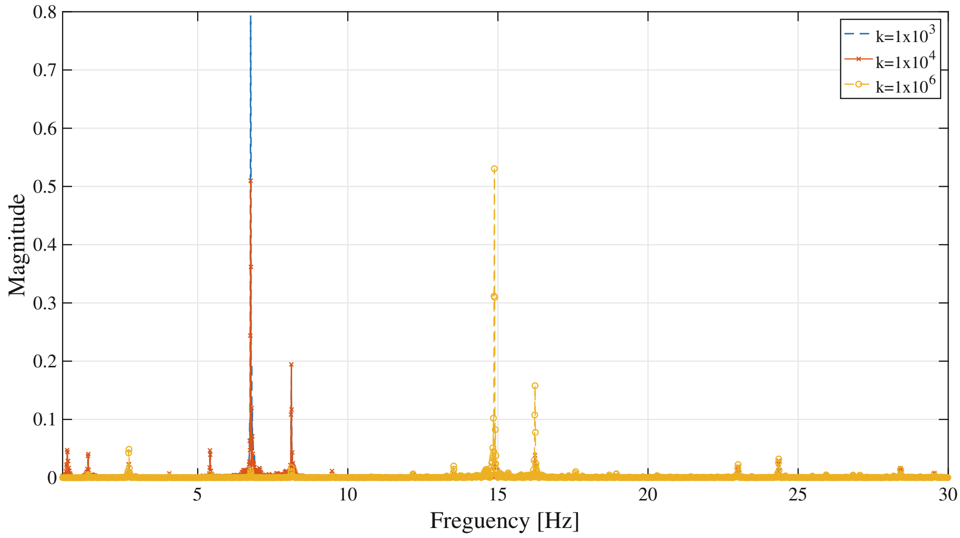


Fig. 7. Fourier Amplitude Spectrum of the loading with V = 50 km/h

the bearing can be assumed to be infinitely rigid while Fig. 8b shows the FAS for the cases where the bearing stiffness is flexible. The amplitudes are plotted in the vertical axes of Fig. 8a and Fig. 8b with a different scale in order to provide the Fourier Amplitude Spectrum of the cases with very stiff bearing stiffness in detail. It can be observed that, the amplitude of the FAS for all bearing stiffesses presented in Fig. 8a and Fig. 8b, are approximately equal to each other at the low frequency ($f < 5$ Hz) region. In other words, the bearing stiffness does not significantly influence the energy content in the first modal frequency of the bridge. On the other hand, the energy in the high frequency region is significantly influenced by the bearing stiffness. Even, when the bearing stiffness is reduced from $k_v = 1 \times 10^{15}$ kN/m to $k_v = 1 \times 10^8$ kN/m (Fig. 8a), the energy at $f = 24.5$Hz increases significantly although the behavior of the bridge



(a) Rigid bearings



(b) Flexible bearings

Fig. 8. FAS of the acceleration time history of difference bearing stiffness for a train speed of 50 km/h

is still dominated by the first mode; see Fig. 8a. When the bearing stiffness is reduced further, Fig. 8b shows that the higher frequency modes start to dominate the behavior and the energy in this region becomes much higher compared to the energy at the first mode frequency. These high frequency vibrations then lead to the high accelerations at the mid-span. As such, although lower bearing stiffness leads to lower bridge natural frequencies (Fig. 2), the amplification in the accelerations are associated with the excitation of the higher frequency modes, more specifically, the third mode of the bridge when the bearing stiffness is reduced below $k_v = 1 \times 10^8$ kN/m.

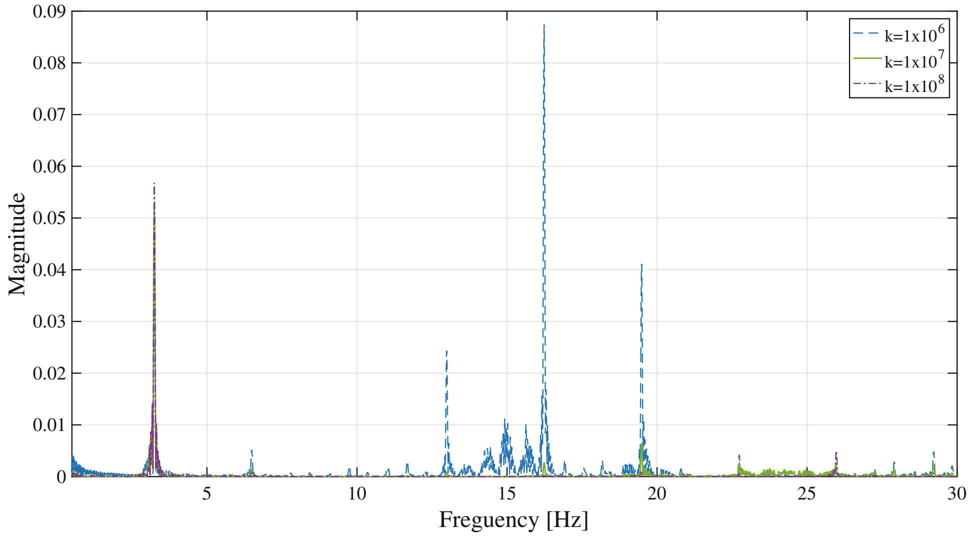


Fig. 9. FAS of mid-span accelerations for a train speed of 120 km/h

The observations summarized in the previous paragraph were made for a train speed of 50 km/h. To investigate if they are applicable for different train speeds, the Fourier Amplitude Spectrum of mid-span accelerations for different bearing stiffnesses for a train speed of 120 km/h was computed and plotted in Fig. 9. This figure depicts that, similar to the case of V = 50 km/h, the behavior of the bridge is dominated by the first mode when the bearings can be assumed to be infinitely stiff. However, the higher modes become more and more dominant with a reduction in the bearing stiffness leading to higher acceleration response at the mid-span.

3 Concluding Remarks

The overarching goal of this ongoing study is to investigate how the changes in the bearing stiffness due to various reasons such as environmental factors, sustained loading, aging and deterioration, can impact the dynamic behavior of railway bridges. This article presents the first set of results from this study and aims to provide a first insight on the effect of vertical bearing stiffness on the dynamic behavior of railway bridges. As a result of the numerical analyses conducted, the following observations can be made:

- The modal frequencies and the dynamic response of the bridge remain unchanged once the vertical bearing stiffness exceeds 1×10^8 kN/m. This value can be treated as the threshold where the bearings become virtually infinitely stiff.
- Once the vertical bearing stiffness drops below this threshold value, the acceleration response at the mid-span increases significantly. Even for the case of $k_v = 1 \times 10^7$ kN/m, where the change in the modal frequencies is subtle, the maximum acceleration response quadruples compared to the infinitely stiff case.

- Exploring the Fourier Amplitude Spectrum of the acceleration responses for different vertical bearing stiffness values reveal that the main difference between the cases with k_v below and above the threshold value of 1×10^8 kN/m is that, for the latter, the behavior is dominated by the first mode. On the other hand, when $k_v \leqslant 1 \times 10^8$ kN/m, higher modes, particularly the third mode, starts to dominate the behavior.
- The natural frequencies of the bridge decreases with a decrease in the vertical stiffness. However, the amplification in the acceleration response is due to the high-frequency response of the bridge with lower vertical bearing stiffness values, and particularly the third mode, whose natural frequency is close to the predominant frequency of the loading when the train speed is 50 km/h.
- The conclusions summarized above is also valid for different train speeds used in this study.

The results provided in this article sheds a light to the complex interplay between the dynamic response of a railway bridge with finite vertical bearing stiffness and the loading frequencies. More detailed analysis including multi-span bridges, different bridge and train properties is required to generalize the outcomes of the study presented herein. Furthermore, acceleration response at different locations of the bridge and its variation with the bearing stiffness and the train properties needs to be investigated.

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