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Jurnal Teknologi Manufaktur

Vol. 14, No. 02, (2022) p-ISSN : 2089-5550 e-ISSN : 2621-3397

Dynamic Analysis on Stainless Steel New Generation Passenger Coach using Multibody Dynamic System

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Received:12 September 2022; Received in revised form:12 November 2022; Accepted:16 November 2022

Abstract

Stainless-steel passenger coaches are the most operated passenger trains in Indonesia, which are manufactured by the Indonesian railway industry, (PT. INKA), from its first launch to the last generation of trains. PT. INKA still keeps innovating to improve the performance of these trains. Nowadays, this passenger coach is being developed to reach a speed of more than 120 km/hour, while keeping the stability, ride quality index, and ride comfort index during operation. This new train would be called a stainless-steel new generation (SS-NG) passenger coach. To reach the target, one of the methods is redesigning the old bogie structure of the stainless-steel passenger coach. The purpose of this research is to design a new bogie for the SS-NG passenger coach and analyze its dynamics during operation at high-speed using multibody simulation. The result was then compared to the existing passenger coach (SS-2018) which was structured by the old bogie one. Sperling's method was utilized for evaluating the ride comfort index of all designed trains. As a result, the SS-NG with a new bogie design showed stable operation and gave an acceptable ride comfort index based on Sperling's method even though travels at 240 Km/h in speed. The results will be important for improving the performance of any train, especially the SS-NG passenger coach which will be fabricated by PT. INKA.

Keywords*: Multibody dynamic simulation; passenger coaches; bogie design; ride comfort index*

Abstrak

Kereta penumpang *stainless steel* merupakan jenis kereta yang paling banyak beroperasi di Indonesia. Hal ini karena kereta ini memberikan fasilitas lengkap, berbiaya ekonomis, dan menawarkan jam operasi yang lebih banyak. Kereta penumpang *stainless steel* difabrikasi oleh PT. Industri Kereta Api (PT. INKA) dari generasi pertama hingga sekarang, dan terus mengalami perkembangan inovasi. Kereta ini sedang dikembangkan agar mencapai kecepatan lebih dari 120 Km/jam dengan tetap menjaga tingkat keamanan dan kenyamanan, serta disebut sebagai kereta penumpang *stainless steel new generation* (SS-NG). Untuk mencapai hal tersebut, salah satu caranya adalah dengan mendesain ulang struktur bogie kereta. Penelitian ini bertujuan untuk menganalisis desain bogie pada rangkaian kereta SS-NG dengan metode simulasi *system multibody dynamic* untuk mengkaji dinamika kereta serta membandingkannya dengan dinamika kereta *existing,* yakni SS-2018. Hasil simulasi menunjukkan bahwa desain bogie kereta SS-NG memberikan tingat kenyamanan pada arah vertikal dan lateral sesuai dengan *Sperling comfort index* pada pusat *carbody*, pusat bogie depan dan belakang saat kereta beroperasi pada kecepatan 240 Km/jam.

Kata kunci: Simulasi *multibody dynamic*; kereta penumpang; desain bogie; tingkat kenyamanan kereta

1. INTRODUCTION

Stainless-steel passenger coaches are the most passenger trains operated on Indonesia's rail lines. This type of train provides complete facilities, such as a passenger capacity of 50 seats per coach, equipped with an air conditioner (AC), dining car, sleeper car with its entertainment media, and provides trips for economic, business, and executive classes [1]. Just for a case, according to the official train ticket sales agent, the ticket price between the station in Purwokerto to the station in Jember which is 661 km away is only IDR 210,000 (about 15 USD) for economical class [2]. In addition, stainless-steel passenger coaches also offer many choices of trip hours, which operates at an average interval of 1 hour for each departure [3].

One of the stainless-steel passenger coaches is shown in Figure 1. This train is manufactured by the Indonesian railway industry, PT. Industri Kereta Api (PT. INKA). This type of train was first launched in 2018 and it was named Stainless-Steel 2018 (SS-2018). At that time, the train was designed for taking a long trip with a maximum speed of 120 km/h and an operating speed of 100 km/hour. PT. INKA continues to improve the performance of those stainless-steel passenger trains. This type of train is now being developed to be able to travel distances at a better speed than before while maintaining stability, riding quality index, and ride comfort index during operation. This new train would be called a stainless-steel new generation (SS-NG) passenger coach.

One of the ways for achieving this target is by designing a bogie structure for the train. Bogie is a wheel unit system in the train that is placed on the rolling stock and the passenger coaches [4]. Generally, there are three bogies which are structured under the rolling stock and two bogies under passenger coaches. The current bogie's structure applied to the stainless-steel passenger train is shown in Figure 2. This type of bogie is applied in the passenger train of SS-2018. As can be seen from the figure, the bogie is a unit where the wheelset and steel frame are connected by a suspension system.

The bogie plays an important role in supporting the structure of the carriage, directing the movement of the train along the rail lines, and keeping the train from derailment, which affects the safety and comfort factors during the travel [5]. Kalivoda & Neduzha (2019) studied the safety level of the train against derailment which is one of the requirements for railroad permits in the EN 14363 standard. They modeled the bogie and the train and then used multibody dynamics to simulate their work [6]. Liu et al., (2012) discussed the cause-and-effect relationship between rail line conditions and derailments which caused accidents. They informed us that most of the derailments were caused by rail line cracks and broken welding areas in rail lines which should be faced by the wheelset of bogies during travel. In addition, a minority of the derailment was due to human error, namely, it did not slow down the train's motion when it passed through a curve rail line [7].

Figure 1. Stainless Steel Passenger Coach Manufactured by PT. INKA [1]

Figure 2. Bogie Structure Applied in Current Passenger Coaches [8]

They claimed that the simulation using a multibody dynamic system was very useful for understanding the behavior of trains during passes the railroad. They used the multibody dynamic simulation techniques for rigid and flexible mechanical structures, including trains. Multibody dynamic simulation applied for the flexible body provided a more detailed analysis than the rigid body one. Pappalardo et al., (2022) developed the nonlinear pantograph scissor lift mechanism using a multibody dynamic system. In their work, several numerical experiments were carried out by employing three multibody programs based on the computational environments relying on MATLAB and SIMSCAPE multibody. It was demonstrating the readiness and the effectiveness of the control methodology which was proposed in the study [9].

Based on those studies, the simulation using multibody dynamic system techniques has been commonly applied to simulate the dynamics of any mechanical system and actually for the train during operation, including determining stability, safety, and comfort. This research aims to analyze the dynamic SS-NG passenger coach which uses a proposed bogie model based on the simulation of the multibody dynamic system. This proposed bogie model is an improvement of the SS-2018 bogie structure. The analysis is then compared to the dynamic SS-2018 passenger coach which used an old bogie model.

Passenger Coaches Modelling

There are two models of passenger coaches applied in the modeling and simulation, namely the model of stainless-steel passenger coach 2018 (SS-2018) which was equipped with an old bogie structure. The other is the model of stainless-steel new generation passenger coach (SS-NG) with a proposed bogie structure model. Those two trains would be compared in their dynamic characteristics; the stability and comfort of the trains, during operating at high speed. The train stability can be calculated by determining the wavelength which was then used to determine the oscillation. Wavelength is determined by the following equation [10] :

$$\Lambda = 2\pi\sqrt{\frac{r_0 l}{\lambda}} \tag{1}$$

where *Λ* is the wavelength, *r₀* is the wheel radius, *l* is the half distance between the two rail lines and wheel contacts, and λ is the wheel conicity.

The comfort level of the train can be analyzed using the Sperling approach, which is a method to measure the wear profile based on the quality of driving at critical speed so that the ride comfort index in the vertical and lateral directions is obtained [11]. The comfort level is divided into various criteria, as follows [11].

Table 1. Ride Comfort Index Level

Ride comfort Index	Vibration Level	Ride Quality
1	Just Noticeable	Very Good
2	Clearly Noticeable	Good
2.5	More pronounced but not unpleasant	Good Enough
3	Strong, irregular but tolerable	Bad
3.5	Very Strong and unpleasant	Not recommended
4	Extremely strong and unpleasant	Danger

The ride comfort index can be calculated by [11] [12]

$$WZ = 0.896^{10}\sqrt{\frac{a^2}{f}}F(f) \tag{2}$$

where *a* is vibration amplitude in cm/s, *f* is the frequency in Hz dan *F(f)* is different frequency weights for vertical and lateral vibrations. Based on Equation (2), it can be written into

$$\sqrt[6.67]{a^2B^2} \tag{3}$$

where *B* is the vertical and lateral comfort direction factors which are written consecutively as follows;

$$B_v = 0.588\left[\frac{1.1911f^2+(0.25f^2)^2}{(1-0.277f^2)^2+(1.563f-0.0368f^3)^2}\right] \tag{4}$$

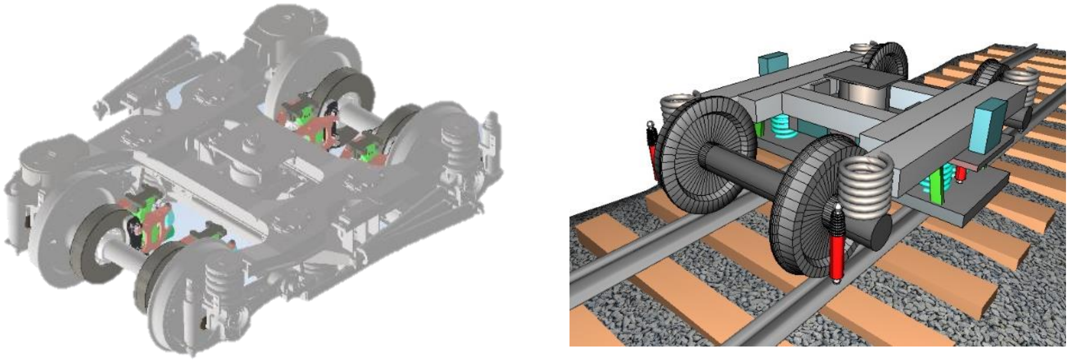
$$B_v = 0.737\left[\frac{1.1911f^2+(0.25f^2)^2}{(1-0.277f^2)^2+(1.563f-0.0368f^3)^2}\right] \tag{5}$$

2. RESEARCH METHOD (Train Mechanical Model and Simulation of Passenger Coaches)

Figure 3 shows the bogie model of the SS-NG passenger coach applied in the simulation. Figure 3(a) is the bogie model in the 3D drawing. This bogie model was then simplified as shown in Figure 3(b) in order to analyze the dynamics of the train during operation. The simplification aims to smooth running in computation and provide more accurate results. As shown in the picture, this model consists of six vertical dampers, one lateral damper, four primary suspensions, eight secondary suspensions in the form of metal springs, and four swing links that are used to connect the bogie frame, bolster, spring plank, and wheelset.

Figure 4 displays a contact model between the train wheels to the rail line in the simulation. The dimensions of the wheel were 0.387 m for the radius, 1.844 m for axle length, 0.565 m for center distance, 1500 kg for the mass, 1.067 m for the width of the rail gauge, and 1: 40 for the wheel conicity. As shown in this figure, the railroad track has a width of 70 mm and these rail lines would be in contact with the wheels while the train is operating in the simulation. Figure 5 displays two passenger coaches that would be analyzed in the simulation; Figure 5(a) is the passenger coach model of SS-2018. Figure 5(b) is the passenger coach model of the SS-NG, the model which is developing in this study. This model has several differences from the old model such as the replacement of rubber springs on the primary suspension, a different bogie frame design, and the addition of a yaw damper.

In addition to the passenger train model as described above, several parameters were required in the simulation. Those parameters are car body mass, bogie mass, train mass, the distance between bogie center and car body center, and distance between bogies, each of which is 31186 kg; 9669 kg; 40855 kg; 7 meters; and 14 m.



(a) (b)

Figure 3. Bogie Model Applied in Simulation : (a) Bogie Model in 3D Drawing, (b) Simplified Bogie Applied in Simulation.

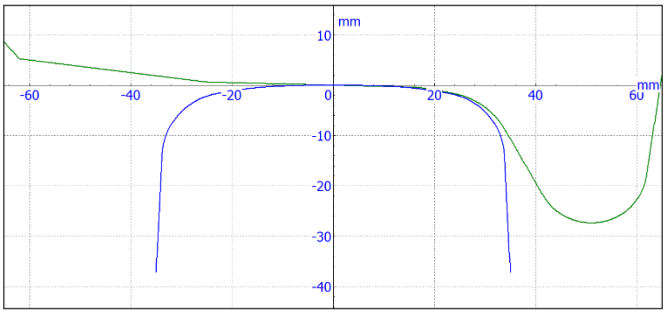
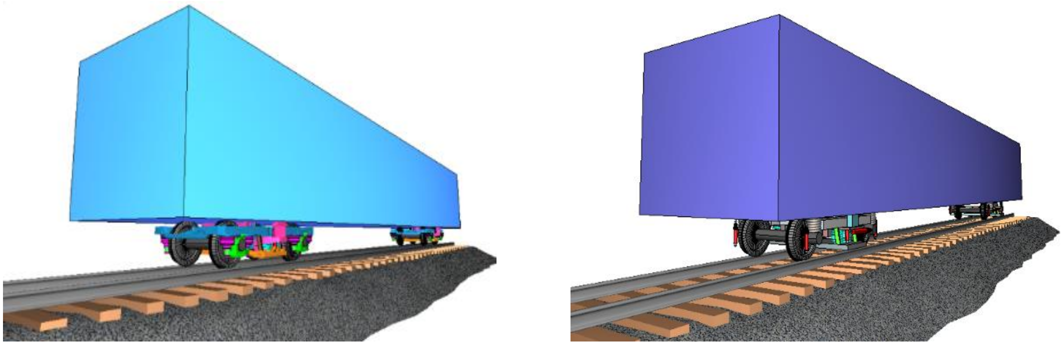


Figure 4. Contact Model Between the Train Wheels and the Rail Line in the Simulation



(a) (b)

Figure 5. Two Passenger Coaches Analyzed in Simulation : (a) Passenger Coach Model of SS-2018, (b) Passenger Coach Model of SS-NG.

3. RESULT AND DISCUSSION

3.1. Simulation of SS-NG Passenger Coach during Critical Speed

Critical speed is an important condition for analysis of the train stability and its instability which is well-known as hunting motion or flutter. This is because the wheel hits the inside of the rail continuously. The critical speed can be analyzed when the train operates at its maximum speed or the train travels in a damaged rail line condition [13]. In this simulation, damaged rail line was simulated by setting the rail line to become little curves with 8 mm in curves. The condition of this rail line would act as a base excitation that excited the train and cause vibration responses. The position of the damaged rail line was placed on both rails located 50 m from the total rail length of 1 km as shown in Figure 6.

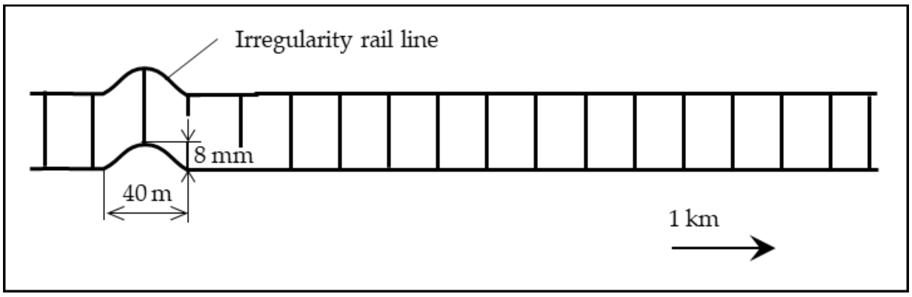
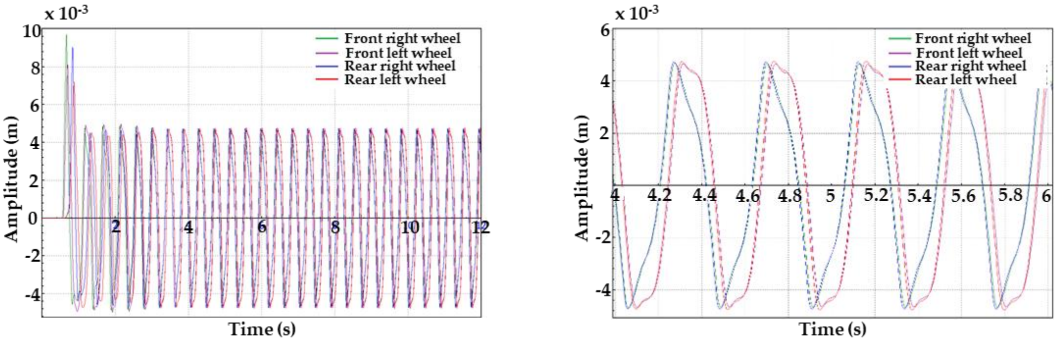


Figure 6. Description of Damaged Rail Line for Achieving Critical Speed

The dynamic condition of the train when it was at a critical speed is shown in Figure 7. In this simulation, the train operated at a speed of 300 km/hour with the lateral damper parameter on the bogie having stiffness and damping coefficient of 4 x 106 N/m, and 6 x 104 N-s/m, respectively. While the condition of the yaw damper parameter also has the same stiffness and damping. Besides, the condition of the rail line which was traveled by train is shown in Figure 6. Figure 7(a) shows vibration responses due to the base excitation in full time. Figure 7(b) shows a snapshot of the full vibration responses that occurs at 4-6 seconds. It can be seen from this picture that there are four vibrations represented by each color. The vibration responses for front bogies are represented by green and violet and the vibration responses for rear bogies are represented by blue and red. It can be seen that the train experienced hunting motion after passing through damaged rail line conditions that occurred for 0.6 seconds. It was indicated that the train was unstable during travel disturbances rail and the oscillation did not decay over time to reach a stable state. From point of view of mechanical vibration, the train is experiencing forced vibration and self-excited vibration. Schmitz and Smith [14] classified that there three kinds of mechanical vibrations; free vibration, forced vibration, and self-excited vibration.

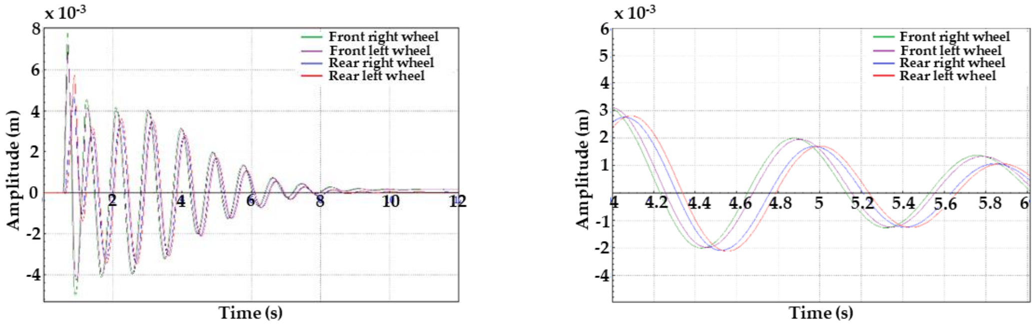


(a) (b)

Figure 7. Vibration Responses of the SS-NG Passenger Coach at Critical Speed : (a) Vibration Response Displayed in Full Time, (b) Snapshot of the Vibration Response that Occurs During 4 – 6 Seconds.

In that case, the stiffness and damping parameters in the bogie of the SS-NG passenger coach need to be increased when traveling at a critical speed. The lateral and yaw dampers on the bogie were, therefore, increased to be 4 x 10^7 N/m for stiffness, and 1.5 x 10^6 N-s/m for damping coefficient. The simulation results after the bogie's stiffness damping coefficient parameters are increased shown in

Figure 8. It can be seen that the train does not experience hunting motion after passing through damaged rail line conditions. Vibratory oscillations decay over time. Besides, the deflection amplitude decreases from 0.01 to 0.008 m. It indicates that the train was more stable comparing the previous bogie model because the train was just having free vibration.



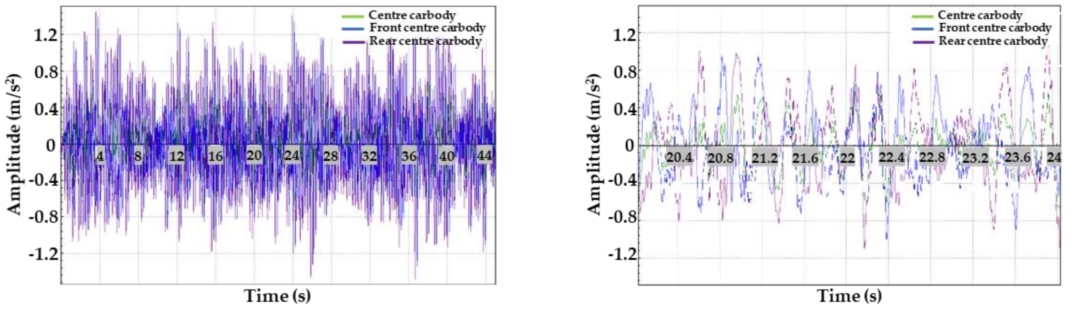
(a) (b)

Figure 8. Vibration Responses of the SS-NG Passenger Coach at Critical Speed With Improved Stiffness and Damping Coefficient : (a) Vibration Response Displayed in Full Time, (b) Snapshot of the Vibration Response that Occurs During 4 – 6 Seconds.

3.2. Comfort index of SS-NG Passenger Coach

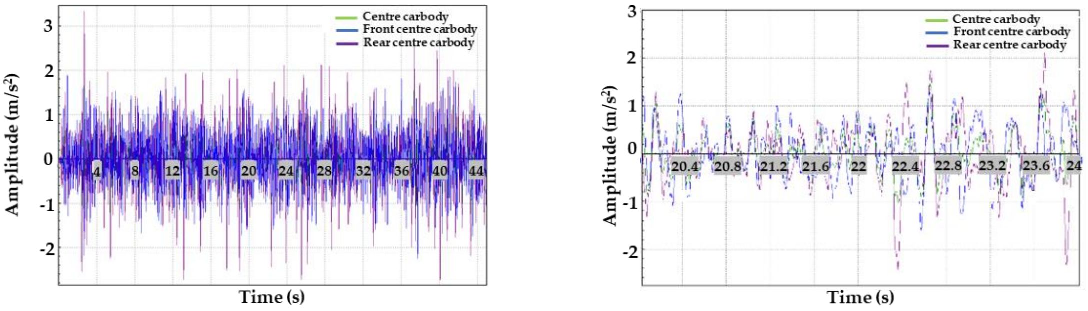
The next simulation is to analyze the comfort level of the SS-NG passenger coach when crossing damaged tracks with a distance of 3 km and operated speed of 240 km/hour. It means that the train is analyzing when it reaches its critical speed. The simulation results are displayed in Figures 9 and 10. Figure 9(a) shows the vertical vibration responses and the lateral vibration responses are shown in Figure 10(a) in full time. It can be seen from the figures that the signal fluctuates over time when the train travels at its critical speed. Besides, the vibrations do not decay over time because the damaged rail tracks excite the structure of train and play as external exciting forces. The vertical vibration amplitude is 1.2 m/s2 and it is lower than the lateral vibration amplitude which is 2 m/s2.

Let us analyze the vertical vibration in detail using Figure 9(b). It can be seen that three vibrations are recognized in these figures which are represented by different colors. The green, blue, and violet vibrations present the vibration belonging to the center of the carbody, front bogie, and rear bogie, respectively. The rear and front bogie vibrations contain high amplitude and the center of the carbody vibration contains the smallest amplitude. It means that this coordinate may have good ride quality index than others. On the other hand, the lateral vibration is analyzed using Figure 10(b). This figure also provides the center of the carbody, front bogie, and rear bogie vibrations. The rear bogie vibration contains a higher amplitude than others. It means that this coordinate may have poor ride quality index than others.



(a) (b)

Figure 9. Vibration Responses in the Vertical Direction When the Train Travels on Damaged Rail Track With Speed Of 240 Km/Hour : (a) Vibration Signal in Full Time, (b) Snapshot of Vibration Signal at 20-24 Seconds.



(a) (b)

Figure 10. Lateral Vibration Responses when the Train Travels on Damaged Rail Track with Speed Of 240 km/hour : (a) Vibration Signal in Full Time, (b) Vibration Signal Snapshot at 20-24 Seconds.

By using the vibration responses, it can then be converted into a comfort value based on the Sperling method as described in Eqs. (2)-(5). Based on the vibration responses, the comfort level of the train in the vertical and lateral directions is shown in Tables 2 and 3. Based on these tables, the comfort level of the train can be well received. This is because the lateral stiffness and damping have been increased as previously discussed, which were increased to 4 x 107 N/m for stiffness, and 1.5 x 106 N-s/m for damping, respectively.

Table 2. Comfort Level Corresponding to Vertical Vibration Based on the Sperling Index for SS-NG Passenger Coach

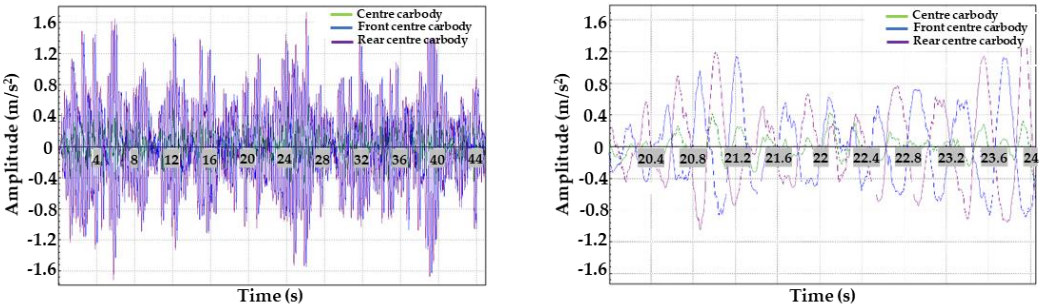
Coordinate	Sperling index	Ride Quality
Centre carbody	1.83	Very Good
Front centre bogie	2.09	Good
Rear centre bogie	2.01	Good

Table 3. Comfort Level Corresponding to Lateral Vibration Based on the Sperling Index for SS-NG Passenger Coach

Coordinate	Sperling index	Ride Quality
Centre carbody	2.18	Good
Front centre bogie	2.47	Tolerable
Rear centre bogie	2.28	Tolerable

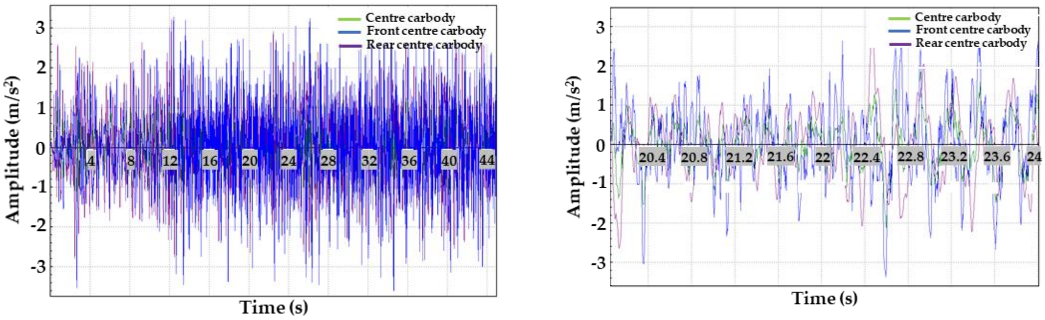
3.3. Simulation of SS-2018 Passenger Coach during Critical Speed

For comparison to the previous results, the comfort level of the SS-2018 passenger coach was simulated during travel at a critical speed. The condition of the damaged rail track and operating speed were the same as in the previous simulation. The simulation results are shown in Figures 11 and 12. The simulation result of the vertical vibration response is shown in Figure 11 and Figure 12 displays the lateral vibration response. It can be seen from the figure that the vibration also fluctuates over time when the train travels at its critical speed. It was caused by the damaged rail track that excites the structure of the train. From the oscillation, it can be seen that the SS-2018 passenger coach is more unstable than the SS-NG train. It is evidenced by the slightly larger vertical vibration amplitude, which is 1.6 m/s2, and also the lateral vibration amplitude is quite larger than the lateral vibration responses generated by the SS-NG train, which is an average of 2 m/s2. Based on the vibration responses shown in Figures 11 and 12, the comfort level is tabulated in Tables 4 and 5. Based on these results, the SS-2018 passenger couch performs worse comfort levels in the vertical and lateral directions. Besides, it was unsafe for running at speed of 240 km/hour because the Sperling comfort index has exceeded the limit of 2.5 in the lateral direction.



(a) (b)

Figure 11. Vibration Responses in the Vertical Direction when the Train Travels on Damaged Rail Track With Speed of 240 km/hour : (a) Vibration Signal in Full Time, (b) Snapshot of Vibration Signal at 20-24 Seconds.



(a) (b)

Figure 12. Lateral Vibration Responses When the Train Travels on Damaged Rail Track With Speed of 240 km/hour : (a) Vibration Signal With Full Time, (b) Vibration Signal Snapshot at 20-24 Seconds.

Table 4. Comfort Level Corresponding To Vertical Vibration Based On The Sperling Index For SS-2018 Passenger Coach

Coordinate	Sperling index	Ride Quality
Centre carbody	1.57	Very Good
Front centre bogie	2.28	Tolerable
Rear centre bogie	2.22	Tolerable

Table 5. Comfort Level Corresponding To Lateral Vibration Based On The Sperling Index For SS-2018 Passenger Coach

Coordinate	Sperling index	Ride Quality
Centre of carbody	2.37	Tolerable
Front of centre bogie	2.67	Bad
Rear of centre bogie	2.63	Bad

4. CONCLUSION

This article discusses the simulation of the SS-NG passenger coach which is being developed and will be fabricated by Indonesia railway manufacturer, PT. INKA. The SS-NG passenger coach will be an innovation from the old version of the passenger coach, the SS-2018. Some important points from the simulation results are summarized as follows :

1. The bogie design of the SS-NG passenger coach was unstable at a speed of 300 km/h during travels at its critical speed. The train was hunting motion and the vibrational oscillations did not decay over time.
2. After the stiffness and damping of the design of bogie were increased, the SS-NG passenger train becomes stable during travel at its critical speed of 300 km/h. Hunting motion and vibrational oscillations were damped after being excited by a damaged rail line.
3. The bogie model of the SS-NG passenger coach was acceptable for design based on the comfort level during travels damaged rail line at a speed of 240 km/h with low vibration amplitude.

4. The SS-2018 bogie model has a poor comfort level based on the sperling index when crossing the damaged rail lines at a speed of 240 Km/h and has a higher vibration amplitude.

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