ON THE INSTABILITY OF THE RAILWAY VEHICLES

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Abstract. The railway vehicles have two sources of instability. The most common is the hunting induced by the reversed conic shape of the rolling surfaces of the wheels. The other one is related by the anomalous Doppler effect that can occurs when the train velocity exceeds the phase velocity of the waves induced in the track structure. Some aspects regarding the two sources of instability are presented.

Keywords: railway vehicle, track, hunting, anomalous Doppler effect, limit cycle

1. Introducere

The railway vehicles experience two kind of instability behavior, one comes from the hunting and the other one is a consequence of the anomalous Doppler effect.

The hunting motion is induced by the reversed conic shape of the rolling surfaces. This motion is passed over to the bogie and to the vehicle body through suspension elements. During the traveling, the hunting is also sustained by track alignment irregularities; therefore, its intensity will be influenced by the amplitude of these irregularities. In addition, the regime of this motion depends on the running speed – at low speeds, the hunting is stable and at high speeds, it becomes unstable. The value of speed when the movement becomes unstable is known as the so-called hunting critical velocity. The cause of the unstable hunting is the creep forces between wheels and rails. The hunting stability and critical velocity were studied using linear models have been used in many papers. Sebeșan [1], Wickens [2], Joly [3] or Lee and Cheng [4] have investigated the influence of different parameters to create a basis for better bogie design. On the other hand, non-linear models were used by van Bommel [5], Pascal [6] and Mazilu [7] to investigate the main feature of the unstable hunting.

The vehicle instability caused by the anomalous Doppler effect is completely different. As already known, this phenomenon may occur when the train velocity exceeds the phase velocity of the waves induced by the train in the track structure. It is really dangerous because, when it begins, the level of vibration increases to such a high value that could affect the track structure and the derailment safety. This unsatisfactory phenomenon is signalled in the particular case of the lines crossing regions with soft soil (peat, organic clays or soft marine clays) [8, 9].

This paper presents some aspects regarding the two sources of instability that are met at the railway vehicles.

2. The hunting

The critical velocity of the hunting \( V_l \) is obtained taking the hypothesis of the linear model – the linear critical speed. When the hunting motion of the vehicle becomes unstable, the oscillation is limited in amplitude by the wheel flanges and a limit cycle occurs. This behavior is influenced by the fact that the wheel and rail are in bi-contact (fig. 1). To point out the features of the unstable hunting, we consider the case of a bogie traveling on a sinusoidal local defect. For the numerical simulation, the parameters of the Y32 bogie have been considered, and a critical velocity of \( V_l = 69.6 \) m/s has been obtained.
Figure 2 shows the lateral displacement of the first wheelset for $V_l = 66.22$ m/s, defect amplitude: $u = 1.9$ mm and defect wavelength $\lambda = 18$ m. The movement is damped and the hunting of the bogie is stable. Fig. 3 presents the lateral displacement of the first axle for $V = 66.22$ m/s, defect amplitude: 2 mm (more precisely, 1.9985 mm) and defect wavelength of 18 m. The movement has a constant amplitude of 6.63 mm and a frequency of 4.34 Hz. The trajectories in plane of the phase are closed curves - limit cycle. The axles do not touch the interior flange of the rail.

If the defect amplitude increases to 2.1 mm, the movement amplitude increases along in time (see fig. 4). As a conclusion, the previous limit cycle (without touching the interior flange of the rail) is unstable. On the other hand, the amplitude of the hunting movement increases until the wheels reach contact with the interior rail flange. The movement becomes again periodic and the phase trajectories are closed curves – another limit cycle was reached. The amplitude of this limit cycle is 8.2 mm for the first axle, and the frequency is 4.82 Hz.
When the wheel flange hits the rail, wheel/rail bi-contact occurs and the rolling surface is unloaded and the flange becomes loaded, increasing the risk of derailment. Fig. 5 displays this interesting aspect for the leading axle. Practically, the wheel/rail bi-contact occurs during a period of 27 ms. The normal force on wheel flange has a maximum value of 38.7 kN. Meanwhile, the normal force on the rolling surface decreases for short time from 64.3 kN to 41.0 kN.

Figure 6 presents the Hopf diagram, the amplitude of limit cycle, either stable or unstable, versus the speed. The bogie hunting has two equilibrium solutions that depend on the value of the speed. For a bogie speed below $V_{nl} = 61.5$ m/s a solution without oscillation is the only existing equilibrium solution. For any initial excitation, the motion will be damped out. Certainly, this sentence remains true if no derailment occurs due to the extremely initial excitation. The speed $V_{nl}$ is the non-linear critical speed.

In the speed range $V_{nl} < V < V_{l}$, there are two stable solutions and one unstable solution. The stable solutions are the equilibrium position and the limit cycle caused by the wheel/rail bi-contact. The unstable solution is the limit cycle without touching the interior rail flange. The existence of this unstable limit cycle shows that the hunting instability may occur even at speeds below the critical hunting speed $V_{l}$ (linear model). The vehicle top speed must be small enough in order to avoid instability debut on accepted geometrical irregularities. In the speed range $V_{l} < V < V_{d} = 77$ m/s there is one stable solution, the limit cycle due to the bi-contact. For a bogie speed above $V_{d}$, the rolling surface is completely unloaded when the wheel smashes the rail and the derailment occurs.

2. Instability due to the anomalous Doppler effect

Considering the case of a force moving along an infinite homogenous elastic structure, the response of the structure at the moving point may be reflected by the equivalent dynamic stiffness. This stiffness depends on the frequency and the force velocity and it is represented by a complex number. The equivalent dynamic stiffness offers details regarding the structure dynamic features. Basically, the mechanical model of the structure at the moving point may
be reduced to one that includes only the concentrated elements (rigid mass, spring and dashpot), according to the sign of the real and imaginary parts of the equivalent dynamic stiffness. There has to be mentioned the possibility of appearance of the ‘negative viscosity’ when the imaginary part takes a negative sign - this possibility is related to the generation of anomalous Doppler waves in the structure. These waves are radiated by a moving object when its velocity exceeds the smallest phase velocity of the radiated waves, and they may generate the unstable vibration of the moving object.

In fact, the explanation of the vibration instability of an object moving along an elastic infinite structure was given by Metrikine [10], who demonstrated that the anomalous Doppler waves increase the energy of the transversal oscillation. The radiation of the anomalous Doppler waves is the only prerequisite for the instability, but not the sufficient one, as the instability is the result of the interaction between the moving object and the elastic structure.

The issue of the unstable response of different kinds of moving sub-systems and elastic structures modelling the railway vehicle/track system has been studied in many papers [11, 12]. The main goal of all these studies is to identify the instability regions in the parameters’ space of the systems considered using the so-called D-decomposition method. However, the dynamic behaviour of the unstable motion, when the sub-system velocity is higher than the critical velocity has not been investigated yet. There are two exceptions, our papers, one of them already published in Journal of Sound and Vibration [13] and other one accepted for publication in the Nonlinear Dynamics [14].

We have considered [14] the case of an oscillator moving along a Timoshenko beam on viscoelastic foundation (fig. 7). This model may be considered as one of the simplest ones for a railway vehicle moving along a tangent track and it may serve to point out the basic features of the stability loss phenomenon, from the qualitative point of view. We have demonstrated that the stability map has two stable regions and two unstable regions (fig. 8).

**Fig. 7.** The uniform motion of an oscillator along a viscoelastic supported Timoshenko beam: (1) oscillator ($M_1 = $ wheel, $M_2 = $ bogie, $M_3 = $ car body); (2) wheel/rail; (3) Timoshenko beam – the rail; (4) extra mass – sleepers and ballast; and (5) viscoelastic foundation – subgrade.

**Fig. 8.** Stability map.
When the oscillator motion along the beam becomes unstable, the dynamic behaviour has two distinct parts: the transitory period and the steady-state period, as seen in Figure 9, where the contact force is presented for the speed of 100 m/s (within the first unstable region). At the beginning of the transitory period, the wheel and the rail are in permanent contact (the contact force is strictly positive), but the amplitudes continuously increase. The vibration frequency is about 7.3 Hz. In the end, the contact loss occurs – this aspect is signalled by the zero values of the contact force - and the dynamic regime is characterised by an exponentially high amplification and the highest magnitudes are registered. Finally, the motion stabilises at lower amplitudes and it shows as a periodic one – the steady-state behaviour.

A detailed time history of this regime can be seen in Figure 10. Note that the positive sense means the upward motion, while the negative one indicates the downward motion, according to the directness of the reference frame. The motion of the moving oscillator/beam system is generated by the action of two contrary factors: the anomalous Doppler waves pushing up the wheel mass and the static load that pushes it downwards. The system vibration is a limit cycle and its frequency is 7 Hz, a value lower than the one in the transitory behaviour, when the wheel and the rail are in a permanent contact. This aspect may be explained by the wheel motion, which is slower while the wheel is flying. The bogie has the highest amplitude. During the impact between the wheel and the rail, the contact force has a very high peak (about 1332 kN) compared to the static load.

4. Conclusions

The railway vehicles have two sources of instability. The most common is the hunting induced by the reversed conic shape of the rolling surfaces of the wheels. The other one is related by the anomalous Doppler effect that can occurs when the train velocity exceeds the phase velocity of the waves induced in the track structure.
The hunting movement of the railway vehicles is caused mainly by the conic wheel profiles and limits the top speed due to its instability. The hunting has two limit cycles: an unstable mono-contact limit cycle and a locally stable bi-contact limit cycle. This last limit cycle is characterized by high accelerations and shocks. The Hopf bifurcation diagram shows that the critical speed (linear) is located between the non-linear critical speed and the derailment speed.

The vehicle instability due to the anomalous Doppler effect takes the shape of a limit cycle. This is the result of the action of the anomalous Doppler waves that force the low mass of the oscillator to take off and the static load that pushes the low mass downwards. In this way, the limit cycle takes the form of successive shocks.

References

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