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ON STABILITY IN HIGH SPEEDS OF MODERN BOGIES WITH ORIENTABLE AXLES

Ioan SEBESAN, Madalina DUMITRIU, Cristina TUDORACHE, Marius SPIROIU
ioan_sebesan@yahoo.com, madalinadumitriu@yahoo.com, marius_spiroiu@yahoo.com, cristi_tudorache2003@yahoo.com

Prof. Ph.D. Ioan Sebesan, Assist.Eng. Madalina Dumitriu, Assist. Eng. Cristina Tudorache, Lect. Ph.D. Marius Spiroiu, POLITEHNICA University of Bucharest, Faculty of Transports, Rolling Stock Engineering Department, 313 Splaiul Independentei, sector 6, 77206, Bucharest,
ROMANIA

Abstract: *The bogie undulation movement is highly important both for the stability of the vehicle, therefore for traffic safety, and for ensuring transversal comfort. The establishment of the traffic speed is essential, in which the stable movement of the vehicle shall transform into an instable movement, namely the establishment of the critical speed, which, once exceeded, results in a quick worsening of traffic. Thus, the maximum speed to be safely attained by a vehicle is actually determined. An improvement in the transversal stability of the bogie and, respectively, an increase in the critical speed may be obtained by a proper construction of the vehicle.*

Key words: *undulation movement, critical speed, bogies with orientable axles, transversal stability of the bogie*

GENERAL CONSIDERATIONS

During the traffic of railway vehicles, at a certain value of the traffic speed, movement transforms from stabile into unstable. If the speed keeps increasing over this “critical” value, traffic worsens quickly. This phenomenon, characteristic for an unstable undulation movement, causes unadmissible transversal stress for the rolling way and endangers traffic safety.

We can say that, of the movements of the bogie, the undulation movement is highly important both for the stability of the vehicle, and, therefore, for traffic safety, and for ensuring transversal comfort.

The speed at which this phenomenon occurs, called critical speed, actually determines the maximum value to be safely attained by a railway vehicle.

The undulation movement is due to the rigid mounting of wheels on the axle and reversed conicities of rolling surfaces. On normal traffic in alignment, if wheels have a wear profile, the axle guidance is made on rolling surfaces and the lips of bandages, in this case, only represent additional safety. With the increase of speed, inertia forces shall occur, which, as they become higher than the maximum force transmittable through the friction wheel – rail, generate the transversal slide of the mounted axle and the takeover of the guidance function by the bandage lip [1].

The transversal stability of the vehicle depends on several factors: the wheel profile, elastic and amortisation features of the suspension, the bogie inertia moment, the suspended mass and the axle base of the bogie, the mass of the axle, etc.

Through a proper construction of the profile of the wheel rolling area and through the accomplishment of axles mounted with low mass and a low inertia moment, the stability range may be extended to high speeds as well.

The undulation oscillations of bogies and the box may mutually influence, by coupling. For reducing the transversal oscillations of the vehicle box, a transversal amortisation must be introduced between the bogie and the box, which is important when the undulation frequencies of the bogie and, respectively, the box, are close.

It is essential that the suspension ensures a decrease, as much as possible, of the movements of the box, respectively coupled staggering and rolling movements thereof. For this, the bogie must be supplied with a "controlled" independence of movement from the vehicle box.

Adopting, for the oscillating system made up of the vehicle box and the central (vertical and transversal) suspension, own frequencies of oscillation, low enough in relation with the frequency of the undulation movement of the bogie, a decoupling of movement is ensured and the risk of resonance at high speeds is avoided, with the frequency of the undulation movement increasing with the speed. Moreover, the box connected to bogies by means of a low rigidity suspension shall exercise moderate dynamic efforts thereon, in a normal mode [2].

Especially important for the dynamics of the vehicle, in transversal direction, is the connection system between the bogie frame and the axle box. The axle driving (guidance) system must transmit the forces operating at a horizontal level, without preventing the operation of the suspension, also ensuring a correct position of the axle on the way and in relation to the vehicle.

The rigid driving system for axles, resulting in an increase of the wavelength in undulation movements, have had satisfactory results up to speeds of approx. 140 km/h. For the improvement of the rolling qualities of vehicles in high speeds, last years' research has oriented towards elastic axle driving systems, with focus on self-guidance possibilities of mounted axles. The new orientation in the conception of bogies consists in creating the aptitude of negotiation of curbing radiuses, by placing axles in a radial position.

Thus, the wear of rolling surfaces and lips, respectively rail flanks, are reduced, but with no undulation instabilities occurring.

In modern vehicles, this is made by means of elastic rubber elements, which, through their own amortisation capacity, contribute to the reduction of the sinus movements of axles, ensuring at the same time a radial location of the axle in curve traffic.

The elastic driving of axles and creation of the possibilities of radial location thereof in curve traffic lies at the bass of the construction of current bogie types for high speeds.

THE EQUATIONS OF THE UNDULATION MOVEMENT OF A BOGIE WITH ELASTIC DRIVING OF AXLES

The undulation movement of a vehicle, respectively a bogie, is very complex. For simplifying the study, the linearization of this phenomenon is pursued, considering that contact forces vary with the lateral displacement of the axle. Moreover, viscous amortisations, frictions, as well as the gaps between the various elements of the bearing structure are neglected, though they all enhance the non-linearity of the phenomenon. The irregularities and discontinuities of the rolling way, which, in turn, influence the undulation movement, shall not be considered.

The linearization of the undulation phenomenon, especially by considering the constant equivalent conicity, proportional to the pseudo-sliding tangential force, will allow for obtaining quality conclusions on the influence of the various parameters on the undulation movement, respectively on the stability thereof.

For establishing the equations of the undulation movement, the mechanical model of fig. 1 shall be used, which presents a bogie in which the suspension of axles is made up of springs with elastic constants c_x , c_y , as well as dampers with linear feature (viscous type), with amortisation constants ρ_x , ρ_y . The bogie mass center is considered as located at the level of axle axes.

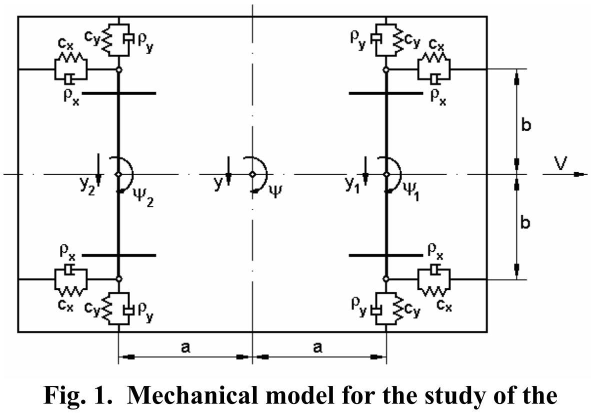

Fig. 1. Mechanical model for the study of the undulation movement

Movement equations are established by neglecting the suspended mass of the bogie, the inertia moment of the mass suspended from the vertical axis passing through the mass center thereof, bogie suspension amortisations $\rho_x = \rho_x = 0$ and admitting the hypothesis of a perfect way, with no lateral derivations. Moreover, the spin effect, the centering of the axle and the gyroscopic effect [1] are neglected. Thus, the oscillating system may be reduced to 4 degrees of freedom.

Noting:

- m_0 the mass of a mounted axle;
- c_x, c_y longitudinal, respectively transversal rigidities of springs in the axle suspension;
- 2a the axle base of the bogie;
- 2e the distance between wheel-rail contact points, for the centered position of the axle on the way;
- 2b the distance between the points connecting the axle suspension;
- r the radius of the rolling circle for the centered position of the axle on the way;
- γ effective conicity;
- χ pseudo-slide coefficient ($\chi_x = \chi_y = \chi$, the pseudo-slide coefficient on a longitudinal direction χ_x was considered equal to the one on transversal direction χ_y);
- $y_{1,2}$ the lateral deviations of axles in relation to the vertical axes crossing the mass centers thereof;
- I_{0z} the radius of gyration of the axle from the vertical axis; v the vehicle's running speed (constant);
- Q load by axle

and, on basis of the previously mentioned simplifying hypotheses, movement equations for the bogie chassis and, respectively, for axles are obtained:

$$
\begin{aligned}
& m_0\, \ddot{y}_1 + (2\,\chi\, Q / v)\, \dot{y}_1 + c_y^* y_1 - c_y^* y_2 - \\
& -(\, c_y^* a + 2\,\chi\, Q)\, \Psi_1 - c_y^* a\, \Psi_2 = 0 \\
& m_0\, \ddot{y}_2 + (2\,\chi\, Q / v)\, \dot{y}_2 + c_y^* y_2 - c_y^* y_1 + \\
& + c_y^* a\, \Psi_1 + (c_y^* a - 2\,\chi\, Q)\, \Psi_2 = 0 \\
& I_{0z}\, \ddot{\Psi}_1 + (2\,\chi\, Q\, e^2 / v)\, \dot{\Psi}_1 + \\
& + (c_x b^2 + c_y^* a^2)\, \Psi_1 - (c_x b^2 - c_y^* a^2)\, \Psi_2 - \\
& -(c_y^* a - 2\,\chi\, Q\, e\, \gamma / r)\, y_1 + c_y^* a\, y_2 = 0 \\
& I_{0z}\, \ddot{\Psi}_2 + (2\,\chi\, Q\, e^2 / v)\, \dot{\Psi}_2 + \\
& (c_x b^2 + c_y^* a^2)\, \Psi_2 - c_y^* a\, y_1 + \\
& + (c_y^* a + 2\,\chi\, Q\, e\, \gamma / r)\, y_2 - \\
& -(c_x b^2 - c_y^* a^2)\, \Psi_1 = 0
\end{aligned}
\tag{1}
$$

where noted

$$c_y^* = c_y c_x b^2 / (c_y a^2 + c_x b^2)\,, \tag{2}$$

meaning an equivalent transversal rigidity.

The establishment of a mathematical expression for the calculation of the critical speed, and, respectively the critical pulsation, may be made on basis of equations (1).

With change of variables

$$
\begin{aligned}
& 2\, y_1^* = y_1 + y_2; \quad 2\, y_2^* = y_1 - y_2; \\
& 2\, \Psi_1^* = \Psi_1 + \Psi_2; \quad 2\, \Psi_2^* = \Psi_1 - \Psi_2,
\end{aligned}
\tag{3}
$$

movement equations become:

$$
\begin{aligned}
& 2\, m_0 \ddot{y}_1^* + \frac{4\,\chi\, Q}{v}\, \dot{y}_2^* - 4\,\chi\, Q\, \Psi_1^* = 0 \\
& 2\, m_0 \ddot{y}_2^* + \frac{4\,\chi\, Q}{v}\, \dot{y}_2^* + 4\, c_y^* y_2^* - \\
& - 4\, c_y^* a\, \Psi_1^* - 4\,\chi\, Q\, \Psi_2^* = 0 \\
& 2\, I_{0z} \ddot{\Psi}_1^* + \frac{4\,\chi\, Q\, e^2}{v}\, \dot{\Psi}_1^* + 4\, c_y^* a^2\, \Psi_1^* + \\
& + 4\,\chi\, Q \frac{e\,\gamma}{r} y_1^* - 4\, c_y^*\, a\, y_2^* = 0 \\
& 2\, I_{0z} \ddot{\Psi}_2^* + \frac{4\,\chi\, Q\, e^2}{v}\, \dot{\Psi}_2^* + 4\, c_x^* b^2\, \Psi_2^* + \\
& + 4\,\chi\, Q \frac{e\,\gamma}{r} y_2^* = 0
\end{aligned}
\tag{4}
$$

For $I_{oz} = m_0 e^2$ and noting

$$A = 4c_y^*(1 - a^2/e^2) + 4c_x b^2/e^2$$

$$B = 4c_y^* \cdot 4c_x \frac{b^2}{e^2}\left(1 + \frac{a^2}{e^2}\right) + 2(4\chi Q)^2 \frac{\gamma}{e\,r}$$

$$C = (4\chi Q)^2 \frac{\gamma}{e\,r}\left[4c_y^*\left(1 + \frac{a^2}{e^2}\right) + 4c_x \frac{b^2}{e^2}\right] \quad (5)$$

$$D = (4\chi Q)^2 \frac{\gamma}{e\,r} \cdot 4c_y^* \cdot 4c_x \frac{b^2}{e^2} + (4\chi Q)^4\left(\frac{\gamma}{e\,r}\right)^2$$

we get

$$\begin{aligned}
&16\,m_0^4 p^8 + 32\,m_0^3 \frac{4\chi Q}{v} p^7 + \\
&+ 8\,m_0^2\left[3\left(\frac{4\chi Q}{v}\right)^2 + m_0 A\right] p^6 + \\
&+ 4\,m_0 \frac{4\chi Q}{v}\left[2\left(\frac{4\chi Q}{v}\right)^2 + 3\,m_0 A\right] p^5 + \\
&+ \left[\left(\frac{4\chi Q}{v}\right)^4 + 6\,m_0\left(\frac{4\chi Q}{v}\right)^2 A\right] p^4 + \\
&+ 4\,m_0^2 B\, p^4 + \\
&+ \frac{4\chi Q}{v}\left[\left(\frac{4\chi Q}{v}\right)^2 A + 4\,m_0 B\right] p^3 + \\
&+ \left[\left(\frac{4\chi Q}{v}\right)^2 B + 2\,m_0 C\right] p^2 + \\
&+ \frac{4\chi Q}{v} C\,p + D = 0
\end{aligned} \quad (6)$$

Considering the stability limit has been reached when $v = v_c$, substituting in equation (6) $p = j\,\omega_c$, finally getting

$$\begin{aligned}
&16\,m_0^4 \omega_c^8 + 8\,m_0^2\left[3\left(\frac{4\chi Q}{v_c}\right)^2 + m_0 A\right]\omega_c^6 + \\
&+ \left[\left(\frac{4\chi Q}{v_c}\right)^4 + 6\,m_0\left(\frac{4\chi Q}{v_c}\right)^2 A\right]\omega_c^4 + \\
&+ 4\,m_0^2 B \omega_c^4 - \\
&- \left[\left(\frac{4\chi Q}{v_c}\right)^2 B - 2\,m_0 C\right]\omega_c^2 + D = 0
\end{aligned} \quad (7)$$

where,

$$\begin{aligned}
&\left(\frac{4\chi Q}{v_c}\right)^2 = 32\,m_0^3 \omega_c^6 / [(8\,m_0 \omega_c^2 - A)\,\omega_c^2] - \\
&- 12\,m_0^2 A\,\omega_c^4 // [(8\,m_0 \omega_c^2 - A)\,\omega_c^2] + \\
&+ 4\,m_0 B\,\omega_c^2 / [(8\,m_0 \omega_c^2 - A)\,\omega_c^2] - \\
&- C / [(8\,m_0 \omega_c^2 - A)\,\omega_c^2]
\end{aligned} \quad (8)$$

relations allowing for the calculation of critical speed v_c and critical pulsation ω_c.

NUMERIC APPLICATION FOR A PASSENGER CAR ABLE TO OPERATE AT A MAXIMUM SPEED OF 200 KM/H, EQUIPPED WITH A BOGIE WITH ELASTIC DRIVING OF AXLES Y 32R

A passenger car equipped with Y 32R bogies was chosen, whose technical and constructive features will be considered in the following calculations: $m_0 = 2000$ kg; $a = 2{,}56$ m; $b = 1$ m; $e = 0{,}750$ m; $r = 0{,}460$ m; $Q = 59650$ N.

A maximum load of the vehicle box was considered for establishing the load by wheel.

P. van Bommel, recommends approximate values of pseudo-slide coefficients [4]. Thus, on basis of the results obtained by *Kalker*, he finds that

$$\chi_x \approx \chi_y = \chi = \frac{300}{\sqrt[3]{Q}} \ldots \frac{400}{\sqrt[3]{Q}} \quad (11)$$

(for Q expressed in tons).

On basis of relation (11) the value of the pseudo-coefficient will be

$$\chi = \frac{300}{\sqrt[3]{Q \cdot 10^{-3}}} \qquad \chi = 76{,}8$$

A special importance for the transversal stability of the bogie is held by the elastic features of the axle driving system. *R. Joly* shows, for speed bogies, with elastic axle driving, the values of $c_x = 10^7$ N/m for transversal rigidity and, respectively, $c_y = 5 \cdot 10^7$ N/m, for longitudinal rigidity [3].

In these conditions, transversal equivalent rigidity

$$c_y^* = c_y \cdot c_x \cdot b^2 / (c_y \cdot a^2 + c_x \cdot b^2),$$

will be $c_y^* = 1{,}481 \cdot 10^6$ N/m.

As mentioned, the wheel profile, through the effective conicity γ thereof, influences the stability of the vehicle. A low conicity generally contributes to the increase of the critical speed, finding that the influence of the effective conicity on critical speed depends on the values of rigidities c_x and c_y. For values of c_x and c_y of more than 10^7 N/m, the effective conicity ranges from 0.10 to 0.15 [1]. $\gamma = 0{,}15$ was adopted in this study.

With the calculation data established as such, on basis of the relations presented above, the coefficients of the equation describing the bogie undulation movement may be calculated:

$$A = 4 \cdot c_y^* \cdot \left(1 + \frac{a^2}{e^2}\right) + 4 \cdot c_x \cdot \frac{b^2}{e^2}$$

$$A = 1{,}46 \cdot 10^8$$

$$B = 4 \cdot c_y^* \cdot \cdot 4 \cdot c_x \cdot \frac{b^2}{e^2} \cdot \left(1 + \frac{a^2}{e^2}\right) + 2 \cdot (4 \cdot \chi \cdot Q)^2 \cdot \frac{\gamma}{e \cdot r}$$

$$B = 5{,}63 \cdot 10^{15}$$

$$C = (4 \cdot \chi \cdot Q)^2 \cdot \frac{\gamma}{e \cdot r} \cdot \left[4 \cdot c_y^* \cdot \left(1 + \frac{a^2}{e^2}\right) + 4 \cdot c_x \cdot \frac{b^2}{e^2}\right]$$

$$C = 2{,}23 \cdot 10^{22}$$

$$D = (4 \cdot \chi \cdot Q)^2 \cdot \frac{\gamma}{e \cdot r} \cdot 4 \cdot c_y^* \cdot 4 \cdot c_x \cdot \frac{b^2}{e^2} + $$
$$+ (4 \cdot \chi \cdot Q)^4 \cdot \left(\frac{\gamma}{e \cdot r}\right)^2$$

$$D = 8{,}75 \cdot 10^{28}$$

Relations (7) and (8) allow for establishing the critical pulsation, respectively the critical speed. Thus, after equation (7) is solved, two real positive solutions of the critical pulsation are obtained, respectively $\omega_c = 20{,}79$ rad/s and $\omega_c = 139{,}4$ rad/s.

According to pulsation $\omega_c = 20{,}79$ rad/s a critical speed is obtained $v_c = 259{,}4$ km/h, higher than the maximum running speed of the vehicle equipped with Y32R bogies, constructively able to operate at 200 km/h.

The obtained results lead to the conclusion that, at a speed of approximately 260 km/h, the undulation movement of the vehicle will become unstable. If the speed keeps increasing over this critical value, traffic worsens quickly, considering that the amplitude of unstable movements increases exponentially.

So, the maximum speed to be safely attained by a passenger car with Y 32R bogies, under the stated loading conditions will be 260 km/h. Considering that bogie Y 32R was conceived for equipping passenger cars able to operate at speeds of up to 200 km/h, the critical speed established in the calculations will not be attained by the vehicle under the scope of this study.

CONCLUSIONS

The relations established, for the study of the undulation movement in bogies with elastic driving of axles, allow for the analysis of the influence of various constructive parameters on the undulation movement and, therefore, establishing the constructive conditions for extension up to speeds higher than the running mode of the transversal stability field.

Simplifications made for purposes of linearization of the undulation phenomenon allow for obtaining quality conditions on the influence of the constructive parameters of the bogie on the undulation movement.

We can notice that an improvement in the transversal stability of the bogie and, respectively, an increase in the critical speed may be obtained by a proper construction of the vehicle, namely by: the reduction of the axle mass and the inertia radius thereof; the reduction of the suspended mass of the bogie; increasing the axle base of the bogie; adopting a low effective conicity; adopting a transversal elasticity of central suspension so as to minimize the influence of bogie undulation on the vehicle box; accomplishing an anti-undulation amortisation lock between the bogie and the box, especially in high speeds. Especially important for the transversal stability of the bogie are the elastic properties of the axle driving system.

The modification of the constructive parameters of the bogie, accomplished for critical speed increasing, will be made considering the fact that newly adopted values may result in increasing the forces exercised on the way in curve traffic.

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ЗА СТАБИЛНОСТТА НА МОДЕРНИТЕ ТАЛИГИ С ОРИЕНТИРАЩИ СЕ ОСИ ПРИ ВИСОКИ СКОРОСТИ

Йоан СЕБЕЖАН, Мадалина ДИМИТРИУ, Кристина ТУДОРАЧЕ, Мариус СПИРОИУ

проф. д-р инж. Йоан Себежан, ас. инж. Мадалина Димитриу, ас. инж. Кристина Тудораче, преподавател д-р Мариус Спироиу Spiroiu, Университет „Политехника" в Букурещ, Транспортен факултет, катедра „Подвижен състав", ул. Индепендентей 313, Букурещ 060042, сектор 6,JA 003

РУМЪНИЯ

Резюме : *Лъкатушещото движение на талигата е много важно както за стабилността на возилото, следователно за безопасността на движение, така и за осигуряване на напречен комфорт. Установяването на скоростта на движение, при което стабилното движение на возилото се превръща в нестабилно движение е съществено, а именно установяването на критична скорост, която веднъж след като е превишена, води до бързо влошаване на трафика. По такъв начин в действителност е определена максималната скорост, която трябва да бъде достигната безопасно от возилото. Подобряването на напречната стабилност на талигата и съответно увеличаването на критичната скорост може да бъдат получена чрез правилна конструкция на возилото.*

***Ключови думи*:** *лъкатушене, критична скорост, талиги с ориентиращи се оси, напречна стабилност на талигата.*