

Analysis of the Mechanism of Longitudinal Flutter of Single Wheel-Set and Related Influence^{*}

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Abstract - The purpose of the study is to analyse the mechanism of longitudinal flutter and related influence by establishing a simplified single wheel-set dynamic model of locomotive. The phenomenon of wheel-set longitudinal flutter is observed at specific speed, after analyse the flutter frequency, found it is nearly the same with wheel set natural vibration frequency, then we put forward a concept of flutter dangerous speed, and a close criterion to calculate the speed is offered. Then discuss the influence of the longitudinal flutter to longitudinal creepage and adhesion utilization coefficient. On this basis, study the impact to the force in wheel/rail contact area and relative sliding at the wheel/rail contact patch; found that the force of wheel/rail contact area was increased significantly; the wheel/rail contact patch relative sliding was quite large, the contact patch adhesion area no longer exists. So we should give more consideration to the vehicle longitudinal influence in the future study.

Index Terms - single wheel-set, longitudinal flutter, dynamic

1. Introduction

Railway vehicle's longitudinal flutter is due to the wheel-set longitudinal flutter, it has become an important reason for abnormal wear. Under normal circumstances a slight out-of-round (OOR) has little effect on vehicle performance [1]. However, many turnings wheel repair is due to fast wheel out-of-round, even cause tread spalling [2], affecting ride comfort and operate reliability. Literature [3-4] proposed measures to reduce wheel tread spalling. The research on DF₂₁ meter gauge diesel locomotive as well as some raising speed locomotive [5-6] found that this phenomenon has great relationship with the wheel longitudinal flutter. Since the axial rod of middle axle in DF₂₁ locomotive use small stiffness, middle wheel sets longitudinal vibration reduce significantly, no peeling occurred, and running very well. For a long time, the railway vehicle dynamics focuses on lateral issues because of wheel/rail lateral self-excited vibration [7]. Over the past decade, the research on the vertical dynamics with the track structure, noise, vehicle-line-bridge, the impact of rail corrugation has carried out detailed [8]. But the current design for railway vehicles at home and abroad, the majority just consider lateral and vertical vibration characteristics, the longitudinal motion was ignored [9], the elastic positioning wheel sets longitudinal vibration characteristics are rarely considered [10]. The longitudinal vibration caused wheel/rail tangential load changes which may lead wheel/rail interface stick-slip vibration [11-12]. As for how it happened is not

known, in other words, the mechanism of longitudinal flutter is still unknown.

In this paper, by establishing a single wheel set model, discover the wheel set longitudinal flutter, and determine the wheel set flutter frequency, then gives a closer criterion to flutter frequency. Analyse the relationship between longitudinal flutter and forward speed, adhesion utilization factor, then proposed a concept of flutter dangerous speed and estimated. On this basis, study the influence of longitudinal flutter to the force in wheel-rail contact area and the relative sliding of wheel/rail contact patch.

2. A Simplified Model of Single Wheel-set

A. Single wheel set model

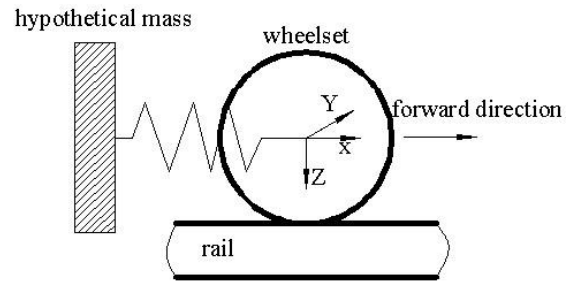


Fig.1 model of single wheel-set

Wheel set has six degrees of freedom, in the model we establish a hypothetical mass, which role is: on the one hand to simulate the positioning base of the wheel-set, the other hand is to increase the critical speed of the wheel set hunting speed, shown as Fig.1.

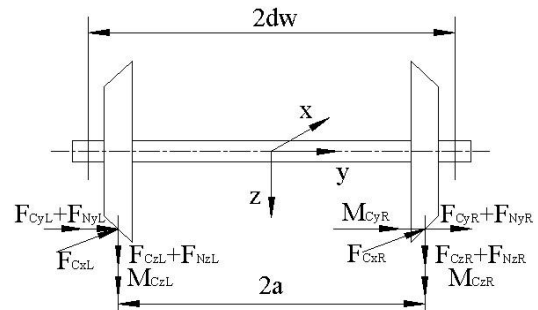


Fig.2 force of single wheel-set

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Fig.2 is the force analysis of wheel-set, according to the force obtained differential equations:

$$m\ddot{x}_w = F_{CxL} + F_{CxR} + F_{SUSPx} \quad (1)$$

$$m\ddot{y}_w = F_{CyL} + F_{CyR} + F_{yL} + F_{yR} + F_{SUSPy} \quad (2)$$

$$m\ddot{z}_w = F_{CzL} + F_{CzR} + F_{NzL} + F_{NzR} + F_{SUSPz} - W \quad (3)$$

$$I_y\ddot{\beta}_{yw} = F_{CyL}r_{iL} + F_{CyR}r_{iR} + M_{CyL} + M_{CyR} + x_{wL}(F_{CzL} + F_{zL}) - x_{wR}(F_{CzR} + F_{zR}) \quad (4)$$

$$I_z\ddot{\psi}_w + I_y\ddot{\beta}_{yw}\dot{\Phi}_w = (F_{CxL} - F_{CxR})a + M_{CzL} + M_{CzR} + M_{SUSP} + a\psi_w(F_{CyL} + F_{yL} - F_{CyR} - F_{yR}) \quad (5)$$

$$I_x\ddot{\phi}_w = I_y(\dot{x}/r)\dot{\psi}_w + r_{iy}(F_{CzR} + F_{NzR}) - r_{iz}(F_{CyR} + F_{NyR}) + M_{CyL} + M_{CyR} + M_{SUSP} \quad (6)$$

In the equations, x_w, y_w, z_w , namely wheel set central displacement of longitudinal, lateral, vertical, F_c, F means creep force and normal force; F_{SUSP}, M_{SUSP} means suspension force and torque; w means axle weight; Φ_w, Ψ_w means wheel set roll angle, yaw angle; a means half of left and right wheel/rail contact point; I_j means inertia of j direction ($j=x, y, z$); r_i means radius of rolling circle ($i=L, R$).

B. Wheel/rail contact relationship

Wheel/rail contact type use JM3 wear tread and 60kg/m, wheel/rail contact geometry is a function of the wheel-set lateral sliding.

C. Parameters of model

Rolling circle radius of wheel is 500mm, axle-box longitudinal positioning stiffness is 1.2×10^7 N/m, lateral stiffness is set to 6×10^6 N/m, vertical damping is 1000 N s/m, the stiffness and damping in the other direction is not set, other parameters shown as Table 1.

Table 1 Relevant model parameters

| Body | Mass/kg | Inertia(x, z)/kg m ² | Inertia y/kg m ² |
|-------------------|--------------------|---------------------------------|-----------------------------|
| Wheel-set | 5000 | 400 | 100 |
| hypothetical mass | 1×10^{10} | 1 | 1 |

D. Track irregularity

The irregularity of the model can be expressed by the following polynomial:

$$F(j\Omega) = \frac{b_0 + b_1 j\Omega}{a_0 + a_1 j\Omega + a_2 (j\Omega)^2} \quad (7)$$

In the equation, $F(j\Omega)$ is a transfer function of wave filter, Ω is function variable, the other variables are non-negative polynomial coefficients. According to polynomial coefficients determined the spatial frequency distribution of track irregularities. Shown as Fig.3.

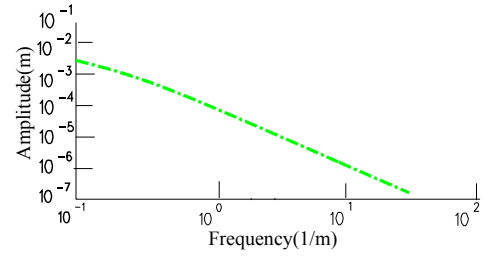


Fig.3 Track irregularity

3. Research on Longitudinal Vibration

A. Longitudinal vibration resonance frequency

The single wheel-set model hunting speed is 40km/h, so we choose the speed 10km/h, 20km/h, 30km/h as simulation, the speed refers to nominal forward speed [14], we find it occurs longitudinal flutter at the speed of 20km/h, we can see the longitudinal vibration acceleration at the speed 20km/h is far more than the running speed of 10km/h and 30km/h. Analyse the model root locus found that there is a frequency does not change with speed, further analyse the vibration frequency, find that this frequency is exactly the wheel longitudinal natural frequency, shown in Fig.4.

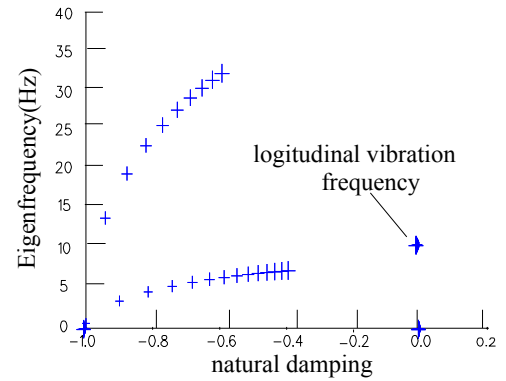


Fig.4 analysis of eigenfrequency

The frequency related with wheel set quality and longitudinal stiffness. According to the work done by Muller, P.C and Schiehlen, W.O [15], we get an approximate estimate of the formula:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{2 \cdot k_x}{m}} \quad (8)$$

m is the wheel set mass in the equation, k_x is axle-box longitudinal positioning stiffness, parameters into the equation:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{2 \cdot k_x}{m}} = \frac{1}{2\pi} \sqrt{\frac{2 \times 1.2 \times 10^7}{5000}} = 11 \text{ Hz}$$

B. Longitudinal flutter velocity

Fig.5 is acceleration spectrum at 20km/h, there is a peak at 10.8Hz. Compared with different speed simulation, this frequency vary with the running speed. the external excitation at 20km/h the wheel-set longitudinal frequency is closer to

longitudinal natural frequency. Moreover, we can regard equation (8) as an approximate criterion whether a vehicle will flutter before it runs.

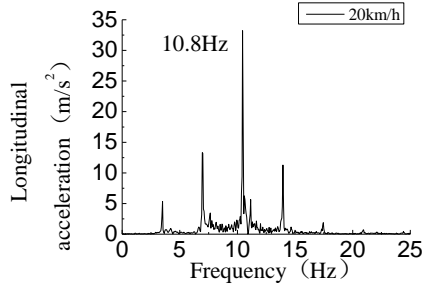


Fig.5 acceleration frequency spectrum

Currently, this formation mechanism which cause the wheel-set longitudinal flutter is not clear[16]. Since wheel set longitudinal flutter or not is specific at different speed, we can get longitudinal flutter has a relationship with velocity. The frequency change with speed can be expressed:

$$f_v = \frac{v/3.6}{2R} \quad (9)$$

In the equation, R is the radius of the rolling circle; v is the forward speed of the wheel-set.

As we all know, the longitudinal natural frequency of the wheel-set is the whole multiple n of the longitudinal vibration frequency who changes with velocity, the wheel-set is more likely to occur the longitudinal flutter, this speed defined as flutter dangerous speed. Obviously, when $n=1$, the flutter dangerous speed reach to maximum, as the critical speed in the model is 40km/h, so choose $n=2$. Then according to the equation (7) and (8), obtain flutter dangerous speed:

$$v = 3.6 \times 2R \cdot f_v = 7.2R \times \frac{f_0}{n} \quad (10)$$

$$v = 7.2 \times 0.5 \times \frac{10.8}{2} = 19.4 \text{ km/h}$$

It is a little deviation with the nominal forward speed 20 km/h, when examine longitudinal velocity component, once ignored by us, find it is 0.6km/h, so we can get flutter dangerous speed is the vector difference between nominal forward speed and longitudinal velocity component.

C. Longitudinal flutter on the longitudinal creepage and the coefficient of adhesion utilization

Analyse the change of longitudinal creepage and adhesion utilization coefficient, value of the longitudinal creepage at 20km/h is far more than the other speeds. Its longitudinal creepage dynamic change is up to 400%. Seen in the Fig.6. in Fig.7, adhesion coefficient often reach saturation at 20km/h, it means wheels slipping, which will not only reduce the performance of vehicles, but also damage the wheel tread[17]. If railway vehicle long-run with longitudinal flutter, then wheel-rail contact patch is at a strong stick-slip vibration, which greatly increase the wheel/rail contact patch

dynamic load, serious deterioration the wheel/rail interface and lead to the wheels wear[18].

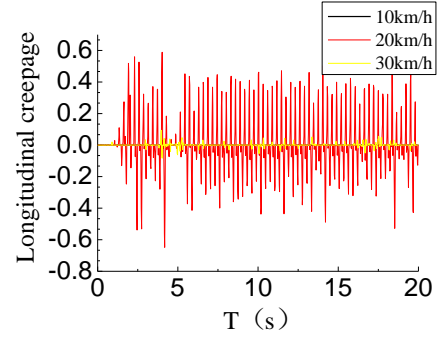


Fig.6 longitudinal creep age

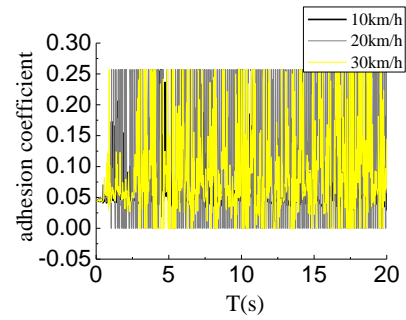


Fig.7 adhesion coefficient

4. Impact of Longitudinal Flutter to the Force on Wheel/rail Contact Area and Wheel/rail Contact Patch Relative Sliding

There are two possibilities of external stimulus to longitudinal flutter: track irregularity or wheel/rail contact patch. However, when remove track irregularities it also occurs longitudinal flutter at 20km/h, shown in Fig.8, the impact of wheel/rail contact patch is the original reason to longitudinal flutter, moreover, formation of longitudinal flutter is a process of time.

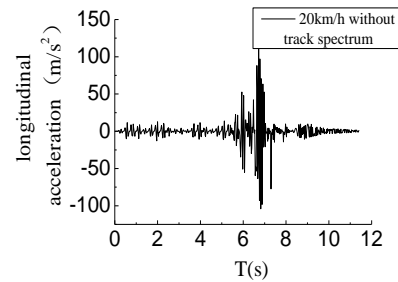


Fig.8 longitudinal acceleration

A. Impact on the force of wheel/rail contact area

Fig.9 shows the longitudinal creep force 3σ value changes with different speeds, when the longitudinal flutter occurs, the wheel-rail contact area longitudinal creep force 3σ value will increase significantly, leading to slippage.

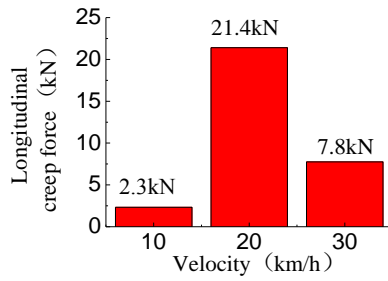


Fig.9 3σ value of longitudinal creep force at different speeds

B. Impact on wheel/rail contact patch relative sliding

Ideally wheel/rail contact patch is an ellipse, which is divided into the sliding area and adhesion area, the relative size change of adhesion area is the wheel-rail contact patch relative slippage which is to be studied. Through simulation the shape change of the wheel/rail contact patch when longitudinal flutter occurs, the contact patch adhesion area nearly disappear, shown as Fig.10, which means relative sliding is very large.

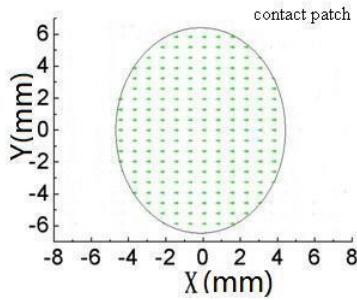


Fig.10 the shape of the contact patch

5. Conclusion

In this paper, we simulate the single wheel-set dynamics simplified model, we can get:

- 1) Longitudinal flutter occurs at specific speed;
- 2) Offer a similar criterion to predict a vehicle will occur longitudinal flutter or not before starting operation.
- 3) Gives an approximate criterion to calculate flutter dangerous speed, and verify the necessary to consider the longitudinal velocity component;
- 4) Longitudinal creep age and adhesion utilization coefficient is increased exponentially when longitudinal flutter occurs;
- 5) Longitudinal flutter has significant influence on wheel/rail contact area, which include increase the wheel/rail contact area creep force and very large wheel/rail contact patch relative sliding;

6) The mechanism of wheel-set longitudinal flutter is the coupling of wheel/rail contact patch excitation frequency and wheel natural frequency.

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