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NONLINEAR DYNAMIC LATERAL RESPONSES OF CURVED RAILWAY TRACK ASSOCIATED WITH HIGH-FREQUENCY SQUEAL NOISES

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Key words: Dynamic Response, Railway Track, Lateral Responses, Curved Railway Track, Squeal Noise.

Abstract. In urban environment, curve squeal is a strongly tonal noise emitted from wheel/rail contact caused by the passage of the train in tight curve rail. Wheel/rail contact can cause a traveling source of sound and vibration, which constitutes high-pitch noise pollution inducing a considerable concern of rail asset owners, commuters and people living or working along the rail corridor. The sound and vibration can be expressed in various forms and spectra. The undesirable sound and vibration on curves are often called squeal noises. This type of noise is commonly emitted in tight curve rails and can be annoying to nearby residents due to its tonal nature and uncertain excitation mechanism. This paper studies the effect of curve radii on the possible occurrence of curve squeal, which is devoted to systems thinking the approach and dynamic assessment in resolving railway curve noise problems. Curve track models in three-dimensional space have been built using finite element package, STRAND7. The moving train loads are applied in order to simulate nonlinear dynamic responses of curve track associated with squeal noise. The simulations of railway tracks with different curve radii have been carried out to develop state-of-the-art understanding into lateral track dynamics. Parametric studies have been conducted to evaluate static and dynamic responses. The dynamic responses of the track are found to be sensitive to the change of curve radii. The resonance peak in the lateral direction is related to the agreement of corresponding natural frequency of rail and the vibration excitation frequency under an individual rolling velocity. The outcome of this study will help provide some key parametric insights into fundamental dynamics of track in the lateral direction and establish the development of the dynamic design of curve track.

1 INTRODUCTION

Railway vibration and noise are a serious concern as it makes an annoyance to people nearby and affects property in the surrounding area [1-3]. Wheel/rail interaction is a traveling source of excitation, sound radiation and vibration along the railway corridors. The sound and vibration can be in various forms and spectra. There are many types of noise occurred on railway track during train passage; ground-bourne, impact, rolling, squeal and flange. However, one of the loudest and most annoying noise sources from railways is squeal noise [4] which is often occurred on curved track. The occurrence of squeal induces significant environmental impacts immensely annoying people living nearby due to its high frequencies characteristics [5]. Curve squealing occasionally arises when railway vehicles run through tight curves at low speed [4, 6]. Table 1 shows different types of railway noise associated with different frequencies. It can be seen that the frequency range concerned with squeal noise is between 1000 and 5000Hz.

Table 1 Frequency range for different types of railway noise [7-9].

Noise type	Frequency range (Hz)
Ground-borne vibration	4-80
Impact noise	50-250 (speed dependant)
Rolling noise	30-5000
Squeal noise	1000-5000
Flange noise	5000-10000

It should be noted that [10-13] unsteady lateral creepage at the wheel/rail contact is thought to be the prime reason of squeal noise, while other mechanisms such as longitudinal creepage and flange contact, do not necessarily eliminate squeal noise thereby are determined to be of secondary importance [14-16]. Previous work indicated that squeal only occur when the curve radius is smaller than 100b, where b is the bogie wheelbase [17]. The results of on-site measurements also presented that there is no significant reduction in wheel squeal associated with limiting operation speed. According to the data collected from fields, it is suggested that diverse range of curving behaviour are largely relevant to curve radii. Although there are many possible treatments [18-20] that can be taken for mitigating the effects of squeal such as improving curving behaviour, modifying rail profiles, adding lubrications or friction modifiers, increasing the damping of wheel or rail, it is still uncertain to what extent the track lateral response is affected by rail radii, cants etc. It is noted that lateral track dynamic characteristic has not been fully investigated. The various curve radii, cants and lateral loads are taken into account in this study.

This paper illustrates the dynamic influences of curve radii, cants, lateral loads on the lateral dynamic vibrations, which are the possible mechanism for development of curve squeal under mode-coupling theory. The study is devoted to systems thinking the approach and dynamic assessment in resolving railway curve noise problems. Finite element package, STRAND7 has been used to build the curve track models in three-dimensional space. The dynamic responses of curve track have been simulated by applying a moving train load. The simulations of railway tracks with different curve radii have been implemented to develop a comprehensive understanding of lateral track dynamics, containing dynamic behaviors of rail, cant, gauge and overall track responses.

2. TRACK MODEL

The track model comprises two-dimensional Timoshenko beam, which takes into account shear deformation and rotational bending effects. This beam has been proven to be the best options for modelling rail and concrete sleeper due to its bending characteristics in both vertical and lateral directions to reflect the behaviour of thick beam [21-22]. It is noted that Timoshenko beam is suitable for solving the problem of beam subjected to high-frequency excitation when the wavelength approaches the thickness of the beam. The 60kg rail cross section (Area: 17659.8mm^2; Second moment of Area: 43.2x10^6) are considered in this track model [23]. While, the trapezoidal cross-section is allocated to the sleeper elements with medium section (204mm top-wide, 250mm bottom-wide and 180mm deep). The non-linear tensionless beam support can be used to demonstrate ballast under the sleeper. It is noted that the tensionless support allow beam to lift over the support while the tensile support is omitted [24]. Thus, this option can correctly reflect the real ballast characteristics [25]. It is noted that the partial support condition is believed to vastly conform with real condition of standard gauge tracks. The rail pads at the rail seat are simulated by using series of spring dash-pot elements. The high-density polyethylene pads are assigned to these spring-dashpot elements both in vertical and lateral direction. It should be noted that the model has been developed and validated previously using experimental parameters, field data and previous laboratory results [26-28]. The finite element models in three-dimensional space for an in situ railway track with both curve and tangent are presented in Figure 1.

Table 2 Material properties.

Parameters	Characteristic value	Unit
Rail		
Length, l_r	10.8	m
Gauge, g	1.5	m
Modulus, E_r	2e5	MPa
Poisson's ratio, v_r	0.25	-
Density, d_r	7850	Kg/m^3
Railpad		
Vertical stiffness, k_{pv}	17	MN/m
Lateral stiffness, k_{pl}	70	MN/m
Sleeper		
Length, l_s	2.5	m
Spacing, s	0.6	m
Modulus, E_s	3.75e4	MPa
Shear modulus, G_s	1.09e4	MPa
Density, d_r	2740	Kg/m^3
Ballast		
Stiffness, k_b	13	MN/m

The curve radius of railway track considered varies from 100m to 600m. Cant is also considered with the range from 100cm to 300cm. It is simplified to 2points loads (1 axle) with a speed of 10m/s and 100kN in magnitude, 2m apart (common passenger bogie centre), on each side of the rail track. The impulse excitations of a period of 0.0001s starting at 0.005s are assigned. In order to cover high frequency squeal noise, the calculation time step is set to be 0.00005. While, the lateral loads are set to be the proportion of vertical loads (Lateral to Vertical, L/V). The schematic lateral load case used is shown in Figure 2.

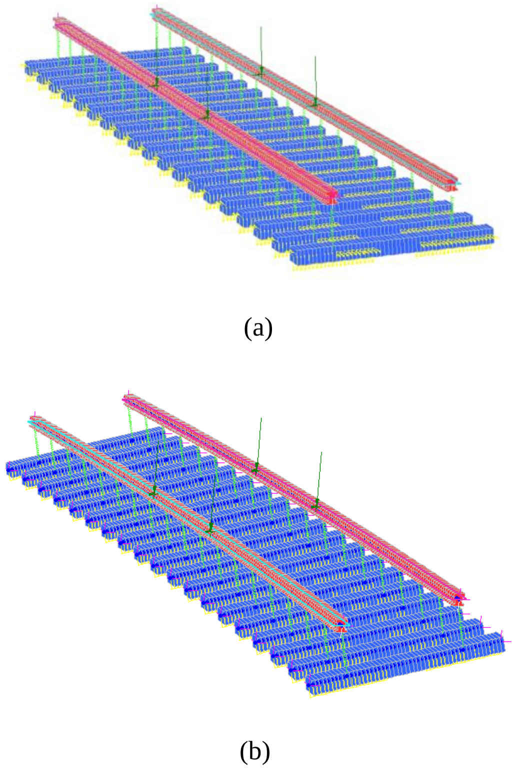


Figure 1 Dynamic track models: (a) The model of curve track (b) The model of tangent track.

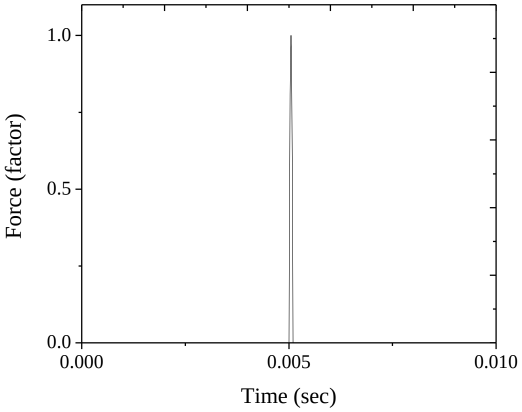


Figure 2 Schematic load case.

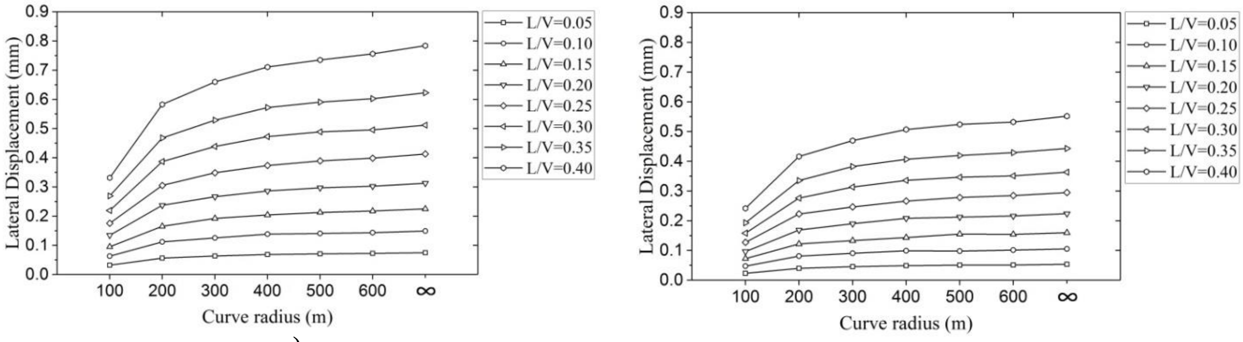
3 RESULTS AND DISCUSSIONS

The Nonlinear Transient Solver in STRAND7 is used to solve the dynamic responses of curved track. The eigenfrequencies and corresponding eigenmodes are calculated up to 10kHz in order to cover modes of squeal noises vastly. For curve track, the parameters concerned are curve radius, cants and lateral loads. The moving loads are applied with the velocity of 10m/s and thus the calculation time of 5s is considered for the whole process. In this study, lateral track displacement, lateral track velocity and lateral track mobility are presented.

3.1 Displacement responses

Dynamic lateral displacements of rail under different lateral load intensity are shown in Figure 3. The vertical loads are fixed to be 100kN as a benchmark for passenger train bogie, while the lateral loads varies from 5kN to 40kN. It can be seen that railway track with higher curve radius or tangent track have severe lateral displacement than that with tight curve. This is because the tight curve has higher lateral resistance and stiffness. It is interesting to note that the trends of rail lateral displacement with respect to curve radius are nonlinear as can be seen in Figure 3. In addition, as for track with 300cm cant, the lateral responses tend to be nonlinear as well as railway track without cant. However, it is noted that the increase of cant can significantly reduce lateral displacement by about 20-30%. As for from 100m to 200m curve radius, about 78% increase of lateral displacement of track without cant is observed. While, only 3.2% increasing rate is expected to occur from 500m to 600m radius. It can be concluded that, for large curve, lateral displacement has a slight change with the increase of radius and thus the radius plays a little role on dynamic response of large curved track but play a significant role on dynamic responses of tight curve. Therefore, the possibility of occurrence of curve squeal noise might be decreased on large curved track.

The obtained results demonstrate that the increase of track radius has a significant positive effect on the reduction of lateral responses which might decrease the possibility of curve squeal. This implies that lateral displacement responses are more sensitive corresponding to low radii, which gave evidence on the appearance of squeal during train negotiating tight curves. It can also be observed from the graph that the lateral track displacement of tangent track is similar to the value of track with a radius of 600m. For large curve radius, the lateral displacement of the track no longer change significantly with increasing radius therefore the increase of radius plays a little role on the dynamic amplitude of track. In reality, this phenomenon is evident from the less flange contact between wheel and rail while train traveling in large curve. The results above indicate that the increased track radius has positive effect on reducing curve squeal and squeal noise would disappear when the curve radius comes to a certain value.

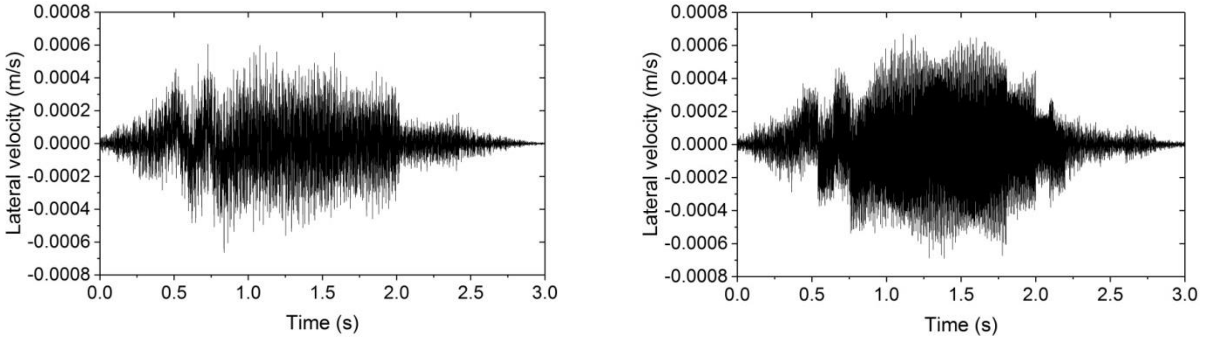


a) b)

Figure 3 Dynamic lateral displacements of track at rail seat with different curve radius a) without cant (b) with 300mm cant.

3.2 Lateral velocity

The time histories of lateral rail velocity are presented in Figure 4. It is noted that the velocity of 10m/s and lateral loads of 20kN are taken into account in this part. Overall, it is shown that the velocity at mid-span is slightly higher than that at rail seat. It is also interesting to note that the peak of the lateral velocity at rail does not occur at the position where train load is applied. This is because there is a delay for the happening of maximum responses. The responses induced by the first sets of loads are smaller than that induced by following train load as a result of the superposition effects of moving loads.



a) b)

Figure 4 Rail lateral velocity of track with 100m radius under L/V=0.2 at a) rail seat b) mid-span.

The dynamic excitations are comprehensively displayed in terms of the lateral mobilities of the track. The lateral mobility spectrums obtained by a fast Fourier transform are shown in Figure 5 as a comparison of three types of track by virtue of logarithmic distribution in dB re.10^{-9} m/s. Overall, it is clearly seen that the curve track with smaller radius has the higher lateral mobilities, in both positions as expected especially between 1000Hz and 5000Hz which is the range of squeal noise. Interestingly, the increasing of curve radius in both cases moves pinned-pinned resonance to higher frequencies and the depth of resonances are effectively reduced. For example, the sharp peaks at 730Hz, which corresponding to pin-pin resonant frequencies, significantly drop by 20dB with the transition of track radius from 200m to 500m.

This is due to the fact that curve radius considerably affects track dynamics. However, in the low frequency range, the lateral mobilites are generally unaffected by the curve radius. As for the frequency range of 1000-5000Hz, the responses from the various cases incur apparently differences due to the influence of wheel/rail interaction during train passage on curve. By comparison with curve track, tangent track globally exhibits much lower noise levels in high frequency, which implies curve squeal is not likely to occur on tangent track.

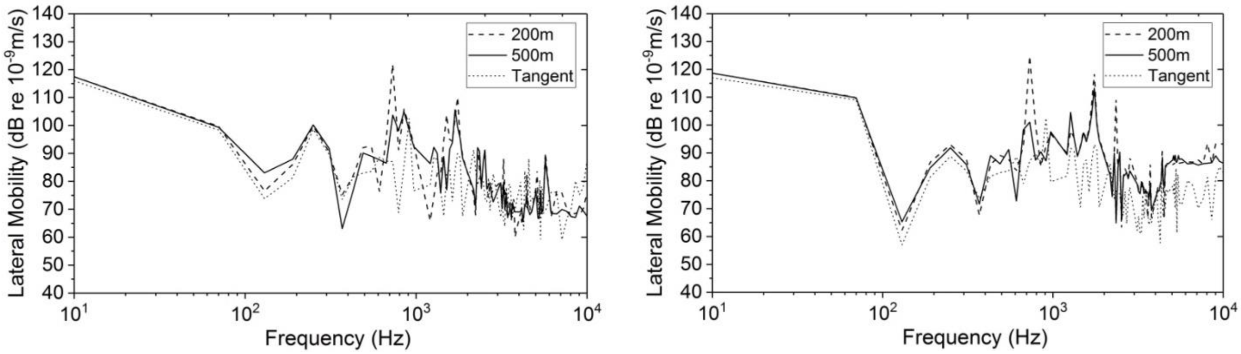


Figure 5 Spectra of the rail lateral mobility at (a) rail seat and (b) mid-span.

4 CONCLUSIONS

In this study, numerical simulation has been conducted to identify the lateral dynamic characteristics of both tangent and curved tracks with the consideration of track radii, cants and lateral loads. Track models have been established in three-dimensional space using a finite element package STRAND7. The results obtained are clearly shown that the increase of curve radius and cants have a positive effect on reducing lateral dynamic responses. The lateral displacement responses are more sensitive corresponding to low curve radii as clearly seen in the results between 100m and 200m radii. It has been noted from the literature that the frequency ranges of between 1000 and 5000Hz are corresponding to the squeal noise. In this region, it is observed that the vibration velocity of 200m radius curved track is lower than that of 500m radius and tangent tracks. Hence, increasing of track radius tends to vastly control the squeal noise at higher frequencies. This study put insight into the dominant influences of different track parameters to track lateral dynamic behaviors. Further studies and more experimental results are needed to investigate associated with these influencing parameters.

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