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Journal of Sound and Vibration 293 (2006) 701–709
JOURNAL OF SOUND AND VIBRATION
www.elsevier.com/locate/jsvi

Curve squeal of urban rolling stock—Part 2: Parametric study on a 1/4 scale test rig

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Accepted 26 August 2005
Available online 10 March 2006

Abstract

This paper is the second of a series of three, dealing with curve squeal of urban rolling stock such as metros and tramways. Measurements were carried out on a 1/4 scale test rig; they include parametric variations on a mono-block wheelset, and tests of anti-squealing solutions. The parametric variations show little influence of load and lateral contact position, except in the case of contact between the wheel flange and the rail, which prevents squealing. A relation between noise level and two kinematic parameters, rolling speed and angle of attack, is confirmed experimentally. The test of solutions leads to the determination of the damping value of the main wheel mode which is needed to suppress curve squeal. The average friction coefficient as a function of lateral creep is measured in dry conditions and with water.

1. Introduction

In a first companion paper [1], after reviewing the current knowledge of the physical phenomena relating to curve squeal, some field measurements on metro and tramway systems are described. The sound pressure levels close to the four wheels of an operating bogie were recorded together with the wheel angle of attack with the track, wheel/rail lateral position and rolling speed. Curve radii were 75 and 60 m, in the first case with mono-block wheels, in the second with resilient wheels.

The main results can be summarised as follows: the inner wheel of the leading axle is the major radiator of squeal noise; the outer leading wheel which is in lateral flange contact does not squeal; pure squeal tones correspond to '0L,*n* type' axial wheel modes; on undamped wheels, squeal sound pressure levels increase in proportion to rolling speed and wheel angle of attack with the rail.

In the present paper, squeal measurements on a 1/4 scale test rig are described. First, the similarity of the test rig compared with previous field conditions is analysed. Then, a more extensive parameter study than is possible with field measurements is performed. The following parameters are investigated: rolling speed, wheel/rail lateral position, angle of attack and vertical load.

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0022-460X/$ - see front matter
doi:10.1016/j.jsv.2005.12.009

In parallel, the test of damped wheels allows determination of the wheel damping required to prevent squealing with good confidence. Finally the friction coefficient as a function of lateral creep is measured in dry conditions and with water.

2. One quarter scale test rig

2.1. Description

The test rig is based on a 13 m diameter wheel of 50 tons (Fig. 1). Two rails are mounted on the circumference. Their profile and the gauge are equivalent to a 1/4 scale track with UIC60 rails. The rotational speed of the wheel can be increased up to almost two revolutions per second, which ensures a maximal tangential speed of 250 km/h.

2.2. Instrumentation

Single 1/4 scale wheelsets are used for measurements which are an exact reproduction of full scale wheelsets (760 mm diameter), including wheel profile and flanges. Two microphones are located 20 mm from the wheels. A laser sensor measures the vibration velocity of wheel 2 (Fig. 2).

The wheelset is supported by a mechanical frame allowing the following parameters to be controlled: vertical force applied on the wheelset (load), angle of attack between the axle and the rails (lateral creep) and relative lateral position between wheels and rails (Fig. 3).

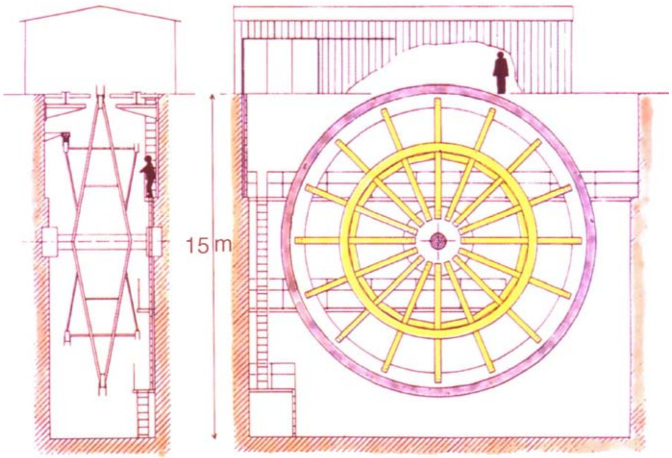

Fig. 1. Big wheel: overview of the test rig.

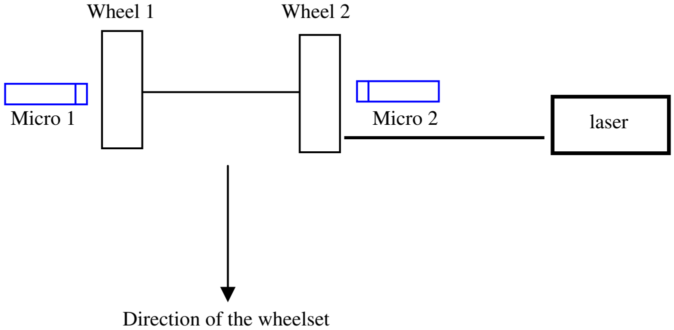

Fig. 2. Diagram of the 1/4 scale wheelset.

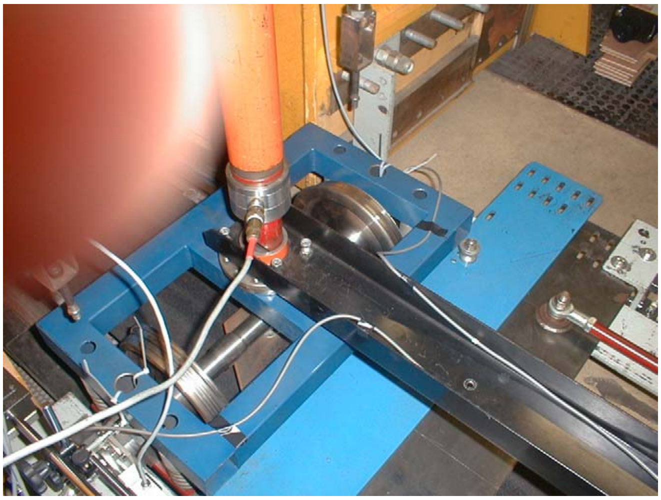

Fig. 3. Top view of the test rig.

Sensors measure all these parameters, including the resulting lateral force between the axle and the rails. The wheelset can either be free or held in position in the lateral direction. The rolling speed depends on the rotation speed of the big wheel.

2.3. Similarity

The rails and the axle under test are at 1/4 scale. The similarity ratios of the main quantities involved in the test rig are listed below:

- Length [L]: ratio 1/4;
- Area [L^2]: ratio 1/16;
- Volume [L^3]: ratio 1/64;
- Mass [M]: ratio 1/64;
- Time [T]: ratio 1/4;
- Speed [$L\,T^{-1}$]: ratio 1 (unchanged);
- Frequency [T^{-1}]: ratio 4;
- Force [$M\,L\,T^{-2}$]: ratio 1/16;
- Acoustic pressure [$M\,L^{-1}\,T^{-2}$]: ratio 1 (unchanged).

The main practical consequences of these similarity ratios are the following:

- The *modal frequencies* of the wheels are multiplied by 4: as pure tones up to 10 kHz can be found at full scale, measurements should be done up to 40 kHz on the test rig.
- The mass of the wheelset under test is divided by 64 compared with the full scale. However, the gravity force should be divided by 16: similarity is therefore not met for the weight. This problem is solved by applying an additional force in the vertical direction, which is equal to $1/16–1/64 = 3/64$ of the weight at full scale. Moreover, this enables various values of axle load to be tested.
- *Pressure* and *speed* are not modified by similarity, whether it is the rolling speed or the vibration velocity of the wheelset.

On the other hand, the scale ratio is not perfectly ensured in the local conditions of the contact, which affect the size of the contact patch and the friction law. The size of the contact patch (surface of contact between the rail and the wheel) can be estimated from Hertz theory. Calculation of the contact ellipse dimensions on the test rig gives ratios between 1/3.7 and 1/3.8 compared with full scale instead 1/4 (Hertz theory is nonlinear).

Wheel and rail rolling surfaces are cleaned regularly to ensure dry and clean friction conditions. Wheel and rail roughness is not measured; however, no significant vertical defects of wheels (new wheelset) or rails were noticed.

3. Parametric variations on a mono-block axle

3.1. Preliminary wheel modal analysis

The wheelset used for these measurements is a 1/4 scale reproduction of a MF77 rolling-stock wheelset investigated during field measurements on a metro system, [1]. A modal analysis was carried out on the 1/4 scale wheelset. The correspondence with the modes recorded on a full scale MF77 wheel is shown in Table 1.

Experimental results are in accordance with theory: the natural frequencies of the reduced scale wheel are 4 times higher than those of the actual wheel.

3.2. Preliminary analysis of wheel squeal

The following observations are drawn from a first analysis of results obtained on the test rig: a good repeatability is found (several successive runs under the same conditions give the same results); during squeal, the wheel is the major noise radiatior (track radiation can be neglected); only one wheel mode is excited during squeal (the 0L,2 mode, other modes with higher values of n—number of nodal diameters—are never excited whatever the rolling conditions; however, when the axle is held laterally—no flange contact on either wheel—some lower modes with $n = 0$ (1240 Hz) or $n = 1$ (1080 Hz) can be excited).

Typical spectra recorded during squeal are shown in Fig. 4: almost all noise peaks recorded close to the wheels correspond to peaks in the wheel lateral vibration velocity measured with a laser sensor. The major part of the squeal amplitude is related to the 0L,2 mode peak arising at around 1730 Hz.

3.3. Influence of angle of attack

The influence of wheel angle of attack with the rail, α, on squeal occurrence is studied first (Fig. 5). This parameter also corresponds to the average lateral creep defined as the ratio between the average lateral sliding speed V_y and the rolling speed V_x.

When the absolute value of the angle of attack exceeds about 8 mrad, wheels start to squeal and the pure tone component related to the 0L,2 mode accounts for a significant part of the overall level. For large positive values of lateral creep (angle of attack >20 mrad), squealing is stopped in this experiment because of a contact between the wheel flange and the rail. This point will be discussed in Section 3.7.

3.4. Influence of rolling speed

Table 2 shows the maximal overall levels recorded on the test rig for various speeds. These levels are also compared with those measured close to the inner front wheel during field measurements on a MF77 metro

Table 1
Correspondence of 0L,n modes (axial mode without nodal circle and with n nodal diameters) between 1/4 scale and full scale wheels

Mode	frequency measured on 1/4 scale wheelset	1/4 scale frequency divided by 4	Frequency measured on MF77 (full scale)
0L,2	1730	430	450
0L,3	4200	1050	1135
0L,4	7900	1980	2020
0L,5	11800	2950	3000

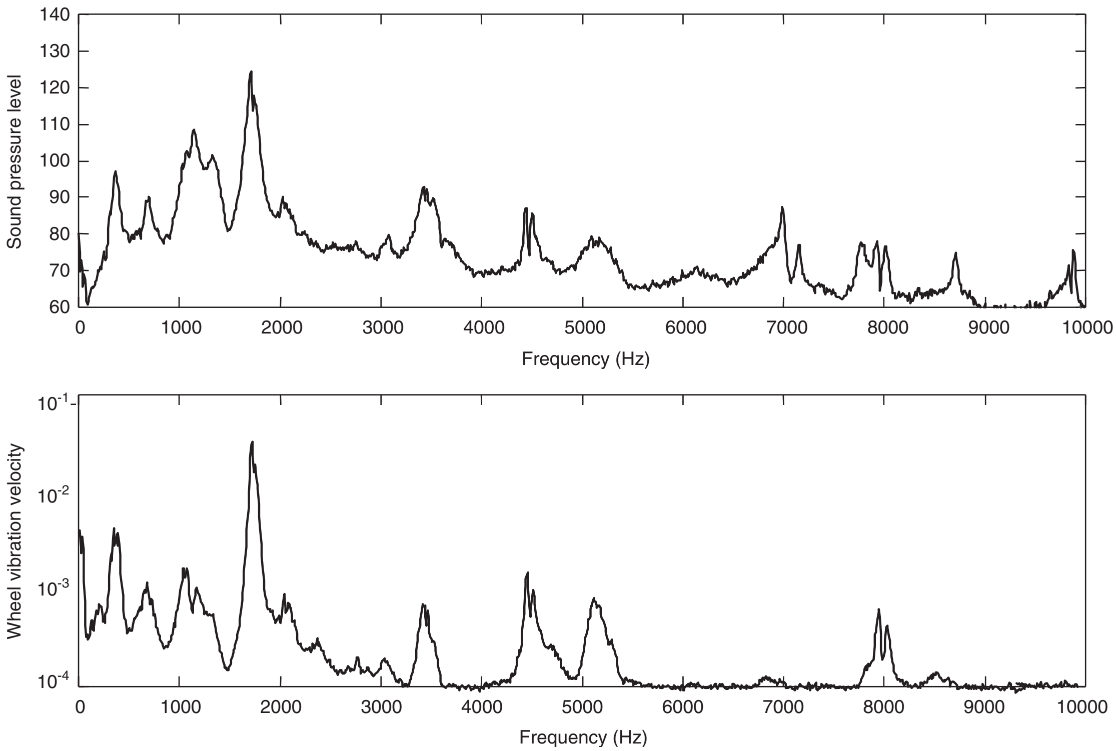

Fig. 4. Averaged spectrum, angle of attack varying from 10 to 35 mrad, rolling speed 20 km/h; upper: sound pressure level measured near wheel 2; lower: vibration velocity of wheel 2, measured by laser velocimeter.

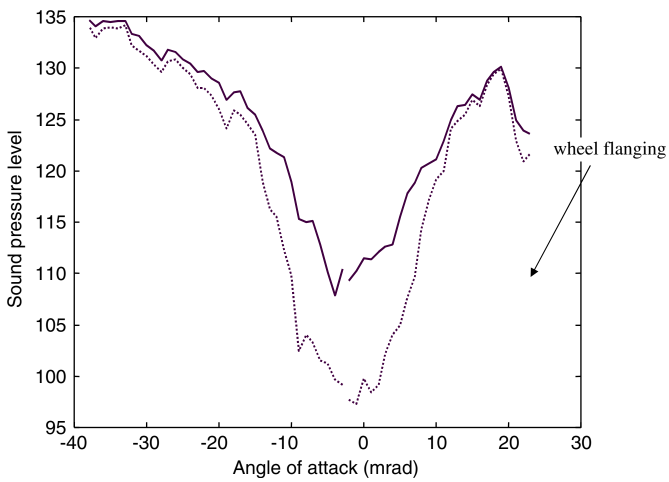

Fig. 5. Sound pressure level of microphone 1 versus angle of attack, rolling speed: 20 km/h. N.B. The reference for 0 mrad is slightly shifted; angle of attack >0: wheelset turns right, angle of attack <0: wheelset turns left. —: overall level 0–10 Hz; - - -: 1.6–1.8 Hz, 0L,2 mode component.

vehicle (second column taken from Ref. [1]). Squeal levels on the 1/4 test rig are close to those recorded during field tests for the higher speeds (30 and 40 km/h). Moreover, sound levels seem to increase in proportion of speed: levels increase by 4–8 dB for a speed doubling. Note that the levels are slightly lower for positive values of angle of attack since wheel lateral flanging contact occurs for an angle of 20–25 mrad on this side (−35 to −40 mrad on the other side), see Fig. 5.

Table 2
Influence of rolling speed on squeal amplitude; unweighted sound pressure levels close to the wheel in dB re 2×10^{-5} Pa

Speed (km/h)	Levels recorded on the field (MF77) Angle of attack = 20–25 mrad	Maximal overall level (dB) recorded on the 1/4 rig Angle of attack = 20–25 mrad	Maximal overall level (dB) recorded on the 1/4 rig Angle of attack = −35 to −40 mrad
10	113	126	128
20	121	130	135
30	132	135	138
40	135	138	141

Table 3
Comparison of measured and predicted sound pressure levels close to the squealing wheel. Unweighted levels in dB re 2×10^{-5} Pa. Values in brackets: calculated values

Speed (km/h)	Measured and (calculated) sound pressure: angle of attack 20–25 mrad		Measured and (calculated) sound pressure: angle of attack −35 to −40 mrad	
10	126	(123)	128	(127)
20	130	(129)	135	(133)
30	135	(132)	138	(136.5)
40	138	(135)	141	(139)

3.5. Squealing noise level versus angle of attack and speed

The following formula relating squeal pressure amplitude close to the wheel p with rolling speed V_x and angle of attack α has been proposed in [1]:

$$p = \rho_0 c \alpha V_x, \tag{1}$$

$\rho_0 c$ being the characteristic impedance of air (400 kg m^{-2} s^{-1}). Table 3 compares measured and calculated sound pressure levels. A fair agreement is found, although measured values exceed calculated ones by 1–3 dB.

3.6. Influence of vertical load

Experiments with increasing vertical loads per wheel ranging from 25 to 60 kN (equivalent full scale values, the actual values on the test rig ranging from 1.56 to 3.75 kN) do not show any significant influence on squeal noise amplitude.

3.7. Influence of the contact position across the wheel tread

No influence of the contact position between the wheel and the rail is observed on the 1/4 scale test rig, except when the wheel flange comes in contact with the rail. To study the influence of flange contact on wheel squeal, the following experiment was carried out: rolling speed and angle of attack were kept constant (20 km/h and 20 mrad, respectively) and an efficient damper was mounted on wheel 1 to prevent squeal. From 0 to 7 s the axle was kept free in the lateral direction: undamped wheel 2 ran in flange contact with the side of the rail. Then, from 7 to 10 s, a lateral force was applied to the axle to remove the lateral flanging of wheel 2. The resulting sound pressure spectra recorded close to wheel 2 are shown in Fig. 6 (microphone 2).

When the wheel flange is in contact with the rail, no squeal is observed. When the wheel flanging is cancelled, squealing appears in the 0L,2 mode (1700 Hz), with noise levels exceeding 117 dB.

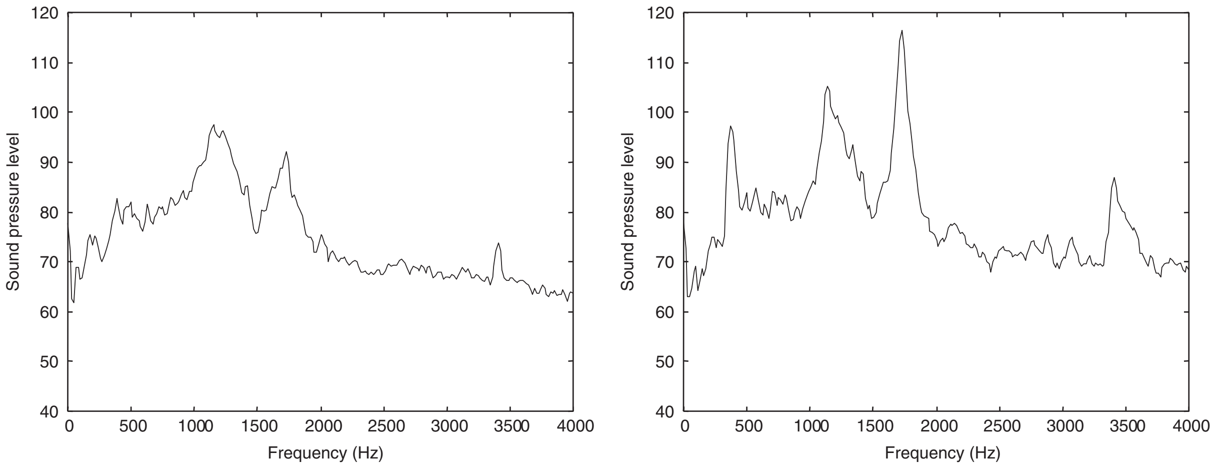

Fig. 6. Averaged spectrum (angle of attack 20 mrad, speed 20 km/h); left: wheel flange 2 in contact with the rail ($t = 4$–$t = 7$ s); right: wheelset centred (no contact between wheel flange and rail: $t = 8$ to $t = 10$ s).

4. Influence of wheel damping

Several existing wheel damping devices such as ring dampers have been built at 1/4 scale and fixed to the test axle. Scale resilient wheels were also tested.

Prior to each test, the damping loss factor of the wheel 0L,2 mode was measured with an impact hammer. The purpose of the test was to determine the amount of damping that is necessary to avoid squealing rather than to test existing technologies (similar damping values are difficult to achieve simultaneously at full scale and 1/4 scale, due to nonlinear effects and geometrical tolerances).

The following results were found: when the damping loss factor (half-power bandwidth measured from the wheel frequency response divided by the frequency, or twice the damping ratio) is less than 1.3%, squealing was always present for high lateral creep values. When the damping loss factor exceeds 3.0%, squealing never appeared.

Therefore, the minimal damping loss factor to avoid squealing on the 0L,2 mode is between 1.3% and 3.0%. Even if not very precise, this result is of great practical interest for rolling-stock manufacturers; a system bringing at least a 3.0% modal damping on the 0L,2 wheel mode can be considered as very reliable to avoid squealing. Moreover, the damping values which are required for modes of higher order (0L,n, $n>2$) can be deduced from the value for the 0L,2 mode by making use of the theoretical formula proposed in the companion paper [2] (see Eq. (15)).

5. Measurement of average lateral friction law

The test rig allows the mean vertical and lateral forces applied to the axle to be measured together with the angle of attack; consequently, the average wheel/rail lateral friction coefficient can be obtained. N.B. the force on each wheel cannot be separated. This coefficient is measured by maintaining the axle lateral position to avoid wheel flanging and by slowly and steadily increasing the angle of attack.

The lateral friction coefficients recorded in dry and wet (water sprayed on the rail) conditions are shown in Fig. 7. Three areas can be made out on the curve: the so-called 'creep area' with a friction force proportional to the angle of attack, the 'saturated area' with a gross wheel slip and an intermediate area linking the two previous ones.

The saturated area starts for angle of attack higher than 8 mrad for dry conditions and about 4 mrad for wet surfaces. The curve slope in the creep area is similar for both conditions.

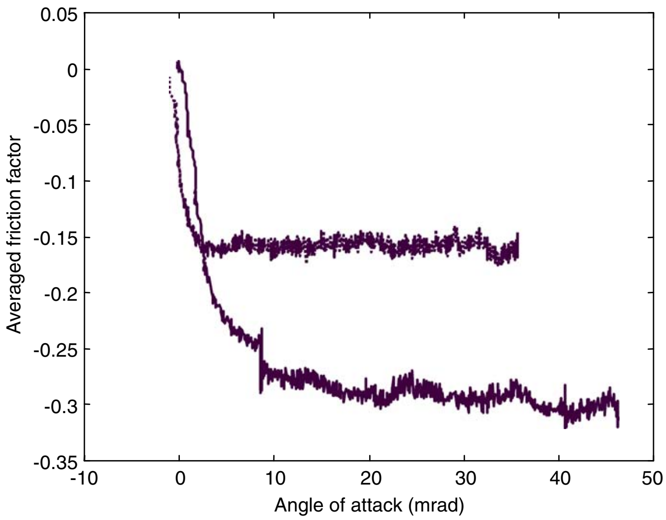

Fig. 7. Average friction coefficient as a function of angle of attack, with and without water N.B. There is no squealing with water, whereas there is squealing without water. — : dry; - - -: with water.

Under gross wheel slip conditions the friction coefficient reaches about 0.3 for dry surfaces and 0.15 with water. In both cases, the curve slope does not show any region of negative slope, although wheel squeal is systematically observed under dry conditions for angle of attack values higher than 8 mrad.

6. Conclusions

6.1. *Influence of key parameters*

With a mono-block wheelset, squealing is reproduced on the test rig with a very good accuracy compared with the full-scale field measurements. Occurrence conditions and sound pressure levels are similar. However the order of excited modes differs: only the 0L,2 mode is found on the test rig, whereas other 0L,n modes of higher order ($n \geqslant 2$) are encountered at full scale [1]. This result may be related to different rail and wheel roughness between the test-rig and actual field conditions since excited modes are sensitive to initial conditions [2].

Two results of the parametric variations of great practical importance can be pointed out: squeal sound pressure amplitudes emitted by undamped wheels increase in direct proportion to rolling speed and to angle of attack, and curve squeal disappears when the wheel flange is in contact with the rail. Both results are in full accordance with the field experiments on a metro system [1]. In addition, the influence of vertical load and lateral contact position (without wheel flange contact with the rail) are shown to be negligible.

Finally, a threshold value of damping of the 0L,2 mode required to prevent squeal occurrence with good confidence is proposed: a loss factor of 3%. Thresholds for the other wheel axial modes with higher order ($n > 2$) can be deduced from this value.

6.2. *Squeal occurrence versus friction law*

In spite of wheel squeal occurrence, no negative slope was observed in the average friction law measured on the test rig under dry surfaces (lateral friction coefficient does not decrease for increasing creepage values). This statement is in apparent contradiction with most theoretical approaches. However, the law relevant for simulation models is the instantaneous contact friction law under transient sliding conditions that cannot be measured easily, whereas the law measured on the test rig corresponds to a quasi-static friction law averaged over several wheel vibrating cycles.

Acknowledgements

This work is part of a French research project focused on curve squeal reduction of urban railways. The authors wish to acknowledge the French Ministries of Research and of Transport for their financial support. Other partners of the project, Alstom Transport, Valdunes and RATP, should also be acknowledged.

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