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Curve squeal of urban rolling stock—Part 1: State of the art and field measurements

N. Vincent[a,*], J.R. Koch[a], H. Chollet[b], J.Y. Guerder[c]

[a]*VIBRATEC, 28 chemin du Petit Bois, 69131 Ecully cedex , France*
[b]*INRETS, 2 Av. Général Malleret-Joinville, 94114 Arcueil cedex, France*
[c]*ALSTOM TRANSPORT rue Baptiste Marcet, 71202 Le Creusot cedex, France*

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Abstract

This is the first part of a series of three papers dealing with curve squeal of urban rolling stock such as metros and trams. After a brief review of the present state of the art, the key parameters involved in curve squeal generation are discussed. Then, some results of field measurement campaigns, on metro and on tramway systems, are presented. A specific measurement methodology is applied for both campaigns in order to record the main key parameters: rolling speed, axle angle of attack, wheel/rail lateral position and modal damping of relevant wheel modes. On-board microphones are mounted close to each wheel of the instrumented bogies in order to locate the squealing wheels. No squeal occurs on the outer wheel of the leading axle in flange contact with the rail. The highest squeal levels are generally found on the front inner wheel. Pure tone frequencies are related to wheel axial modes for metro (undamped steel wheel) and for tramway (resilient wheels). Squeal occurrence is also observed on a bogie with independent wheels.

1. Introduction

Curve squeal turns out to be one of the prime sources of nuisance of urban rolling stock such as metros and light rail systems. In the frame of a French research project aiming to pave the way to cost-effective solutions for squeal control, an extensive investigation of relevant parameters has been carried out from 2000 to 2003. Some results of this project are presented in three associated papers.

In this paper (part 1), after a review of the state of the art, the main parameters accounting for curve squeal occurrence are discussed. Then, a preliminary parametric investigation based on measurement campaigns under controlled conditions on metro and tramway systems is presented.

In the second paper a more extensive parametric study performed on a 1/4 wheelset scale model is presented [1]. Finally, a simulation model is built and numerical simulations are compared to experiments [2].

*Corresponding author. Tel.: +33 4 72 86 65 88; fax: +33 72 86 65 66.
E-mail address: nicolas.vincent@vibratec.fr (N. Vincent).

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2. State of the art

Curve squeal of railway rolling-stock can be defined as follows: high noise levels with pure tone components occurring in sharp curves. This can be expanded upon as follows:

High noise levels: sound pressure levels up to 130 dB can be recorded close to the wheel, and up to 100–110 dB at 7.5 m from the track centre [3,4]. Squeal noise levels can exceed usual rolling noise levels by more than 15–20 dB.

Pure tone components: the predominating part of squeal noise energy is related to the occurrence of one or several pure tone frequencies ranging from about 400 Hz to more than 10 kHz according to the rolling conditions [3,5].

Occurrence in sharp curves: normally squeal noise does not occur for curve radius R higher than 500 m and the risk for squeal increases for radius lower than 300 m. Several authors have introduced the R/W ratio (W being the wheelbase i.e. the distance between the two wheelsets of the bogie) as a relevant indicator to account for curve squeal occurrence [5,6].

A R/W ratio lower than 100 would provide a high squeal probability without specific mitigation measures. This rule would give a curve radius limit of about 200 m for a 2 m wheel base which is a common value for tram and metro bogies.

Moreover, curve squeal is often seen as an erratic phenomenon that can be strongly influenced by small variations of operating or weather conditions.

2.1. Overview of main physical phenomena

The following steps can be identified to account for squeal noise generation: excitation at wheel/rail contact, wheel and rail vibration response, wheel and rail radiation.

2.1.1. Excitation

Wheel lateral creepage is considered as the prime cause of squeal generation [3,6,7]. Most bogies are made of non-steerable parallel axles. Consequently, both wheelsets cannot be tangent to the rail when traversing a curve and an additional lateral sliding velocity V_y is added to the longitudinal speed V_x. The resulting lateral creepage, defined as the ratio between lateral and rolling velocities, initiates lateral contact forces. In steady state conditions, the average lateral creepage on one wheel can be considered to be equal to the angle of attack α, defined as the angle between the wheel and the rail tangent directions. For small angles, one has:

$$V_y = \alpha V_x. \tag{1}$$

Rough simplifications of the geometry in tight curves allow an estimation to be made of the angle of attack versus geometric parameters; the following formula is given in Ref. [6] as applying to the leading axle:

$$\frac{W}{2R} \leqslant \alpha \leqslant \frac{W}{R}. \tag{2}$$

The upper limit W/R is reached on the leading axle when the trailing axle is nearly radial to the track.

Most authors agree to relate squeal occurrence to a wheel/rail friction law (lateral force versus lateral creepage) with a negative slope for high creep values [3–14]. This point will be discussed in the two companion papers [1,2].

On the other hand, the effect on squeal of longitudinal creepage related to differential travelling distance on inner and outer rails is widely considered as secondary.

In the same way, flange rubbing occurring on the outer wheel of the leading axle is generally not considered as the leading excitation mechanism. However, additional experimental results are still required to confirm this point.

2.1.2. Wheel and rail vibration response

Generally, the wheel contribution in vibration response and sound radiation exceeds that of the rail [3,6]. This result is likely to be related to the higher lateral mechanical receptance of the wheel at the contact: unlike the rail, the wheel presents many lightly damped natural frequencies in the lateral direction that lead to a much higher receptance than the rail [3,8]. On the other hand, the rail exhibits a non-modal damped behaviour (infinite structure strongly connected to the foundation).

The pure tone components arising are generally related to wheel natural frequencies: in most cases, these frequencies correspond to the 0L,n modes [8] (i.e. out-of plane wheel bending modes with no nodal circle and with n nodal diameters).

Simulation models indicate that, during squealing, the wheel lateral vibration velocity amplitude at the contact should not exceed the lateral average sliding velocity V_y [9,10].

2.1.3. Wheel noise radiation

The geometrical parameters of wheels lead to a radiation efficiency close to 1 for axial modes above 600 Hz: wheel web thickness is usually greater than 20 mm, leading to a critical frequency lower than 600 Hz (for steel). Radiation efficiencies ranging from 0.5 to 1.5 have been computed numerically [11].

By taking a radiation efficiency equal to 1 and by assuming that the lateral vibration velocity amplitude of the wheel at the contact is equal to the average lateral sliding speed V_y, the sound pressure level close to the wheel (say less than 0.1 m) can be approximated by

$$p = \rho_0 c \alpha V_x, \tag{3}$$

$\rho_0 c$ being the acoustic impedance of the air.

2.2. Key parameters and associated solutions

Three classes of key parameters accounting for curve squeal can be identified: the local kinematic parameters at wheel/rail contact, the contact friction law and the wheel modal parameters.

2.2.1. Local kinematics parameters

Neglecting the longitudinal sliding effect, three basic kinematic parameters are identified: the rolling speed V_x, the attack angle and the lateral position of the contact across the wheel tread.

The angle of attack and lateral position parameters are directly related to the bogie and track design features. Angle of attack is considered as the key kinematic parameter influencing squeal: a threshold value of about 7–9 mrad is often stated in the literature: above this value, curve squeal is very likely to occur in a current situation with no mitigation measures [6,12]. This value corresponds well with the criteria based on the R/W ratio (a R/W value of 100 gives a W/R value of 10 mrad); the threshold value of 7 mrad is situated between the two limits defined by Eq. (2). Typical values for urban systems are the following: R ranging from 25 to 200 m for tramway tracks and 75 to 300 m for metro tracks; W ranging from 1.6 to 2.0 m for tramway bogies and from 2.0 to 2.4 m for metro vehicles.

The lateral position can also influence the squeal occurrence, especially in the case of high values corresponding to wheel flange contact [12]. In most cases, the flanging contact seems to bring a positive effect on squeal control: for instance, a railway operator such as RATP claims a 100% efficiency on squeal control by only watering the inner rail of curves (the outer wheel of the leading bogie is always under a situation of flanging contact for a sharp enough radius).

The speed can be considered as a secondary parameter compared to creep although it can affect squeal occurrence and amplitude [13].

Angle of attack can be reduced by a narrowing of track gauge, by soft primary suspensions or by a reduced bogie wheelbase. However, the curve radius remains the dominant parameter: a bogie design with steerable axles is the only way to prevent high lateral creep values in the case of urban networks with sharp curves.

2.2.2. Contact friction law

Many anti-squeal treatments are based on the alteration of wheel-rail friction law: two types of treatment can be found on existing networks: the use of an additional lubricant and rail surface treatments.

Anti-wear on-board systems with a spray of lubricant focused on the wheel flange during curving can certainly reduce curve squeal; however, such systems do not seem to be sufficient to eradicate squeal [13].

Rail watering is an efficient means to prevent squeal; however troublesome secondary effects such as severe rail fatigue and high maintenance costs are generally observed [13]. Top of rail friction modifiers seem to be efficient to reduce wheel squeal [4,13].

Treated rail with an additional welded strip on the rail head are usually found on sharp curves of tramway lines; this solution reduces and sometimes eliminates curve squeal [13].

2.2.3. Wheel modal parameters

Since railway wheels exhibit a highly modal behaviour, the wheel receptance at the contact can be fully described by wheel modal parameters. Attention should be given to increasing the damping value of axial modes that prove to be a key contributor to curve squeal. No precise threshold for damping loss factor can be extracted from existing publications.

Many damping devices are currently available on the market with different levels of efficiency: resilient wheels commonly used on tramways, friction systems added on the wheel, constrained layer systems and dynamic absorbers [13].

3. Field measurements on metro

3.1. Introduction

The purpose of the field measurements was to collect data in squealing conditions and to determine the influence of key parameters on squeal occurrence and noise level. The measurements were made on a metro bogie (MF77 rolling stock) in Paris in November 2000. The anti-squealing systems of the four wheels were removed and the brake systems were taken out of service. The wheels are monobloc with a very low damping (wheel nominal diameter of 860 mm).

The most interesting data are those measured in a 75 m radius curve which was operated at four different speeds (10, 20, 30 and 40 km/h) in both directions: direct and reverse on the same track. The vehicle was under slight power to keep the speed stable during each test. The bogie under investigation had a wheelbase of 2.2 m giving a R/W value of 34 (W/R value of 0.029); this value is far below the squeal threshold of 100 presented earlier.

3.2. Instrumentation

A specific set of on-board measurement devices was used to record the main data identified as key parameters: train speed, angle of attack and wheel/rail lateral position. Wheel modal parameters were measured on one wheel before the running tests. For practical reasons, the lateral friction law was not measured.

The instrumentation essentially consisted of 4 microphones, located close to the outer lateral side of the wheel tread of each wheel in the bogie (0.1 m laterally from the tread, at mid-height of the tread, at the top of the wheel side); four accelerometers mounted laterally, at mid-height of the wheel web, with a radio transmission system; and four position sensors, located ahead and behind the two wheels of the leading axle for the direct runs (and then on the trailing axle for the reverse runs—Fig. 1) measuring location relative to the rail. The position sensors used an eddy current technology. The wheel/rail lateral position and the angle of attack are given respectively by averaging and subtracting the signals of the two sensors of the wheel.

Each microphone was intended to characterise one wheel, but the three other wheels may interfere in the signal. The accelerometers were used to quantify the discrimination power of the microphones. Thanks to their position on the outer side of the wheels, as will be seen, the influence of other wheels on a given microphone was reduced by at least 15 dB.

3.3. Preliminary modal analysis of one wheel

The natural frequencies of axial modes with no nodal circles and with more than 1 nodal diameter measured on one wheel of the test bogie are given in Table 1. Measured damping loss factors for all modes were found to be below 0.04%.

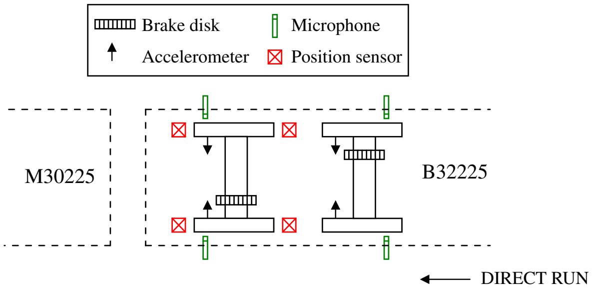

Fig. 1. Diagram of instrumentation on metro vehicle.

Table 1
0L,*n* type modal frequencies (axial mode without nodal circle and with *n* nodal diameters) of MF 77 monobloc wheel

Mode	Modal frequency in Hz
0L,2	450
0L,3	1135
0L,4	2020
0L,5	3000
0L,6	4040
0L,7	5100
0L,8	6170

3.4. *Identification of squealing wheels*

Three runs were recorded for each speed. Tables 2–5 present sound pressure levels measured with the on-board microphones and averaged along the whole curve (on-board sound pressure levels measured close to the wheels were quite steady along the curve). The results presented in these tables show a good repeatability of acoustic levels for all speeds.

The highest noise levels are always related to the inner wheel of the front wheelset. On the other hand, levels on the other three wheels are more than 15 dB below that of the front inner wheel for all runs at 30 and 40 km/h. For lower speeds, at 10 and 20 km/h, the rear inner wheel appears to squeal, but with lower levels than the front inner wheel.

A similar analysis has been made for 12 reverse runs for speeds ranging from 10 to 40 km/h: the same results are found. The highest noise levels were radiated by the inner leading wheel. Similar noise amplitudes were recorded.

3.5. *Identification of emerging frequencies*

A frequency spectral analysis was performed on the 12 direct runs under study. According to the run and to the bogie position along the curve, three modes arise: the 0L,2, the 0L,3 and the 0L,4 modes.

A time–frequency analysis of the on-board microphone located close to the front inner wheel is shown in Fig. 2: the 0L,2 mode is excited firstly during a small portion of the curve. Then, the 0L,3 mode predominates along a short section. Finally, the 0L,4 mode with upper harmonic components predominates along most of the curve length. The amplitude of the second harmonic (twice the wheel mode frequency) is about 20 dB below that of fundamental frequency. Higher harmonics can be noticed but their amplitudes remain below the second harmonic.

3.6. *Account of kinematic parameters*

Values of the three kinematic parameters related to the leading (front) axle are visualised in Fig. 2 in parallel to the sound pressure levels. It can be noted that the angle of attack (or average lateral creep) varies between

Table 2
Average sound pressure levels versus wheel position in dB re 2×10^{-5} Pa—speed 10 km/h

Run	Inner front	Outer front	Inner rear	Outer rear
1	114.2	98.1	99.8	98.4
2	111.8	101.2	105.5	97.6
3	113.5	101.6	106.1	98.7

Table 3
Average sound pressure levels versus wheel position in dB re 2×10^{-5} Pa—speed 20 km/h

Run	Inner front	Outer front	Inner rear	Outer rear
1	125.4	108.7	110.7	108.5
2	119.1	108.5	111.1	106.3
3	119.4	109.1	111.0	106.8

Table 4
Average sound pressure levels versus wheel position in dB re 2×10^{-5} Pa—speed 30 km/h

Run	Inner front	Outer front	Inner rear	Outer rear
1	132.3	115.9	115.8	111.0
2	132.0	115.5	115.8	110.9
3	132.6	116.3	116.4	110.8

Table 5
Average sound pressure levels versus wheel position in dB re 2×10^{-5} Pa—speed 40 km/h

Test	Inner front	Outer front	Inner rear	Outer rear
1	135.1	118.4	118.7	114.4
2	134.6	118.6	118.9	114.5
3	134.7	118.4	118.6	114.7

25 and 30 mrad; this value is in agreement with the expected values ranging from 15 to 29 mrad derived from the W/R ratio, see Eq. (2). Moreover, the lateral position of the inner wheel is about 20 mm from the centre, which confirms that the outer wheel flange is in contact with the rail.

Table 6 gives the angle of attack and sound pressure levels of the front inner wheel, averaged over the whole curve and for the three runs, for the four speeds under investigation. The sound levels close to the wheel are compared with those estimated using Eq. (3): a good agreement is found for 30 and 40 km/h whereas the measured levels stand about 8 dB below the predicted ones for lower speeds (10 and 20 km/h).

4. Field measurements on tramway

4.1. Test conditions

Measurements were performed on the Grenoble tramway network in February 2001. The test train included two motor bogies with rigid wheelsets and one trailer bogie with independent wheels (Fig. 3). All wheels are resilient (Bochum wheels) with a 640 mm nominal diameter. The bogie wheelbase W is 1.9 m.

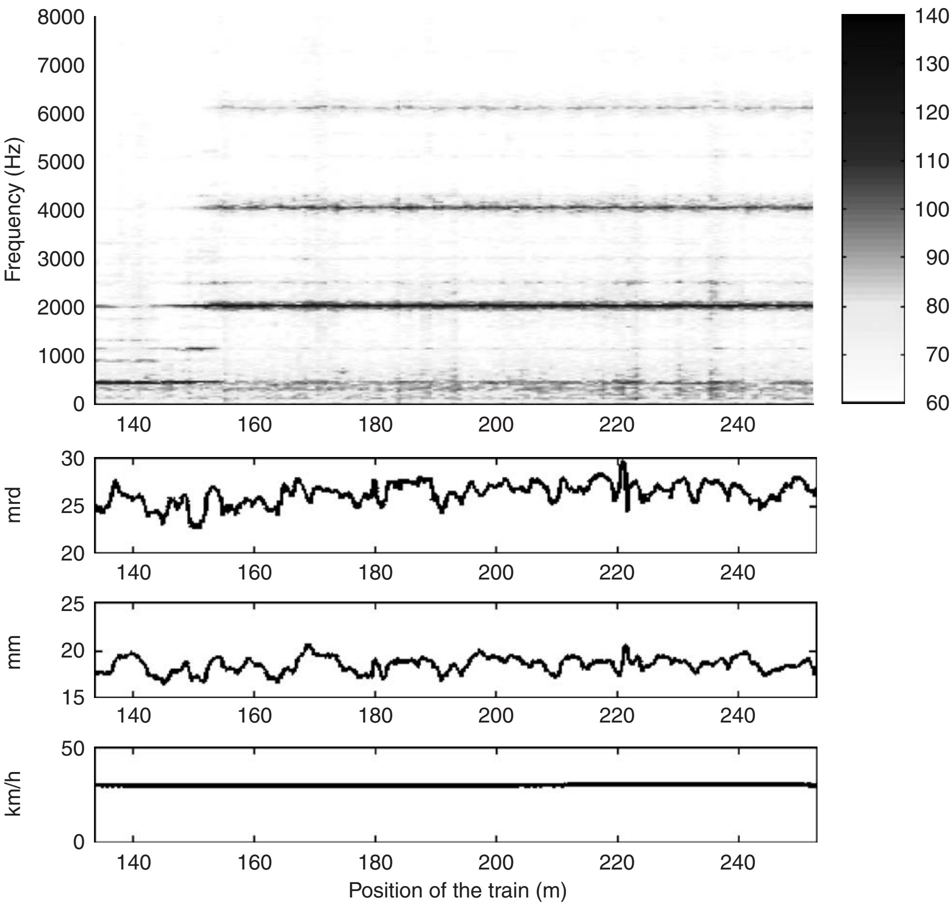

Fig. 2. Squealing in the 75 m radius curve; from top to bottom: sonogram of the microphone near to the front inner wheel; angle of attack of the front axle; lateral position of the front inner wheel; speed (30 km/h).

Table 6
Averaged angle of attack and sound pressure levels of front inner wheel versus speed

Speed (km/h)	Angle of attack of front axle (mrad)	Sound pressure level in dB near the front inner wheel	Estimated noise level from Eq. (3)
10	20 (−8.3)	113	121
20	25.4 (−3.6)	121.3	129
30	26 (−2.1)	132.3	133.6
40	26.1 (−1.5)	134.8	135

Values in brackets: angle of attack of the instrumented wheelset when rolling in reverse direction.

The eight wheels of one motor bogie and of the trailer bogie were instrumented with microphones located less than 0.1 m from the wheel outer side (position at mid-height of the wheel tread, on the top part of the wheel side). The lateral position and angle of attack of wheel 1 (motor bogie) and wheel 5 (trailer bogie) were also recorded.

Measurements are focused on a 60 m radius curve consisting of grooved rails treated with an anti-squeal welded strip. The vehicle was under slight power during the tests in order to keep the speed stable. The curve radius and wheel-base gives a R/W ratio of 31.5, far below the threshold of 100 (W/R value of 31 mrad).

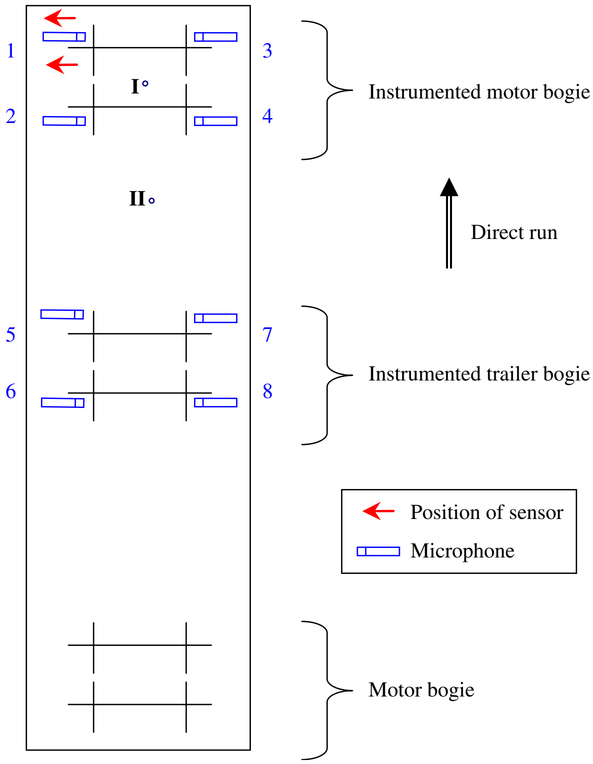

Fig. 3. Instrumentation on tramway vehicle.

4.2. *Preliminary modal analysis of one wheel*

As for the metro tests, an experimental modal analysis was carried out on one wheel. The modal parameters of the 0L,n modes involved in wheel squeal are given in Table 7. The highest damping loss factor of 1.6% was measured on 0L,2 mode.

4.3. *Identification of squealing wheels*

Two successive runs were recorded for each speed: a good repeatability is found; therefore only averaged values are presented in Tables 8 and 9. The sound pressure levels recorded by each microphone are averaged over the curve length (about 60 m).

On the motor bogie, wheel squeal *only occurs on the front inner wheel* and only at low speed: 10 and 15 km/h. Sound pressure levels lower than 100 dB are likely to be related to rolling noise. Similar results are found on the reverse runs, the results of which are not shown here.

On the trailer bogie with independent wheels, *the front inner wheel squeals* for speeds ranging from 10 to 20 km/h for direct and reverse (not shown) runs. For the higher speeds, the outer rear wheel becomes the only squealing wheel (observed on direct runs only).

4.4. *Identification of emerging frequencies*

Spectral analysis is made for all recorded runs. All 0L,n modes, n ranging from 3 to 9, were excited. Several modes can be excited simultaneously although a single mode seems to predominate at any one time. The 0L,2 mode was never excited.

Table 7
Modal parameters of a tramway resilient wheel—0L,n modes

n	0L,n	
	Freq (Hz)	Damping 2C/Cc (%)
2	436	1.6
3	1268	0.8
4	2264	0.4
5	3344	0.9
6	4486	1.0
7	5644	0.7
8	6844	
9	8085	

Table 8
Averaged sound pressure levels in dB re 2×10^{-5} Pa, four wheels of motor bogie, direct run

Speed in (km/h)	Outer front	Inner front	Outer rear	Inner rear
10	103.1	**120.8**	96.9	104.3
15	98.7	**115.2**	94.3	97.0
20	98.8	96.6	93.7	92.8
25	96.7	92.7	93.3	92.4
30	98.7	96.3	97.6	96.8
35	98.8	97.2	98.6	98.1

Values in bold indicate squealing.

Table 9
Averaged sound pressure levels in dB re 2×10^{-5} Pa, four wheels of trailer bogie, direct run

Speed in (km/h)	Outer front	Inner front	Outer rear	Inner rear
10	96.4	**113.1**	102.4	102.3
15	96.7	**113.0**	104.5	102.3
20	99.4	**110.4**	**114.0**	101.2
25	96.5	98.7	**111.9**	93.8
30	99.9	99.5	**112.5**	97.7
35	99.1	99.9	**106.7**	98.6

Values in bold indicate squealing.

4.5. *Account of kinematic parameters*

For all speeds, a steady angle of attack around 40 mrad was recorded on the leading axle of the motor bogie. This value is greater than the expected limit of 31 mrad defined earlier in Eq. (2). The time analysis of records at the beginning and at the end of the curve indicates that squeal does not appear for angles of attack below 25 mrad.

Noise levels recorded close to the squealing wheels are much lower than the upper limit defined by Eq. (3) which gives: $L_p = 127$ dB at 10 km/h and 130 dB at 15 km/h (for an angle of attack of 40 mrad).

5. Conclusions

The field investigations can be summarised as follows.

5.1. Position of squealing wheel and influence of flanging

On the metro system, the highest squeal levels were always observed on the inner wheel of the leading axle. No squeal was found on the two outer wheels; this result is in agreement with RATP experience (stating that watering of the inner rail of sharp curves is sufficient to prevent wheel squeal).

On the tramway, the front inner wheel of the motor bogie was also the highest squeal radiator. Squeal also occurred on the trailing bogie with independent wheels: at low speed, the front inner wheel also prevailed whereas at higher speed squeal occurred on the rear outer wheel only.

During the metro and tram tests, squeal was never observed on the leading outer wheel which was in flange contact with the rail.

5.2. Squeal amplitude versus lateral sliding speed and pure tone frequencies

On the metro system with monobloc undamped wheels, sound pressure levels close to the front inner wheel are in agreement with amplitudes estimated using Eq. (3). Noise levels seem to increase in proportion to the average lateral sliding speed $V_y = \alpha V_x$. On the tramway with resilient wheels, noise levels remain much lower than the limit given by this formula. On both the metro and tramway systems, the squeal frequencies always correspond to wheel axial modes 0L,*n*.

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