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SONIA: AN ENGINEERING TOOL FOR RAILWAY CURVE SQUEAL ANALYSIS

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ABSTRACT

Curve squeal is due to the imperfect curving behavior of rolling stock and is typically related to the inner leading wheel, which slips laterally on the rail. This may cause a non-linear instability leading to self-sustained wheel vibrations and by consequence, loud and tonal sound emission. This is perceived as highly annoying by line side residents and is a major noise problem for railways in urban areas. In order to evaluate potentially critical situations (e.g. change of rolling stock) or to design mitigation solutions (e.g. wheel dampers), VibraTec developed an engineering tool called SONIA (Squeal Occurrence NoIse Analyzer).
Based on the characteristics of wheel, track, as well as the kinematic, contact and friction conditions, SONIA can predict if curve squeal is likely to occur. A stability analysis of the mechanical interaction of the wheel-rail system is carried out, using linearized contact forces. If curve squeal occurs, the sound power associated to each unstable frequency is estimated: the amplitude of the limit cycle is calculated through a balance between the injected and the dissipated power within the wheel-rail system.

Keywords: *curve squeal, railway, simulation.*

1. INTRODUCTION

Curve squeal noise is a highly annoying phenomenon that mostly concerns urban railway networks, e.g. tramway, metro, commuter trains. Complaints by nearby residents drive network operators to take into account curve squeal noise in procurement specifications and/or to implement mitigation solutions. Rolling stock manufacturers are increasingly faced with strict specifications in terms of curve noise and curve squeal noise in particular. As a consequence, both network operators and rolling stock manufacturers need simulation tools to quantify the risk of squeal, and to design mitigation solutions without having to rely on extensive measurement campaigns. Engineering tools allowing to carry out fast and user-friendly simulation are still not available. That is the motivation for the development of SONIA (Squeal Occurrence NoIse Analyzer) tool.

Curve squeal is a loud tonal noise that occurs when a train negotiates a sharp curve. In those cases, large angles of attack are experienced, thus leading to lateral slip at the wheel/rail contact (Fig. 1).

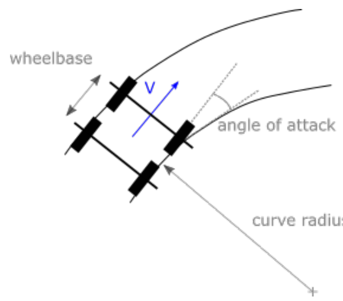

Figure 1: Railway curve negotiation.

Friction forces at the contact cause self-sustained vibrations of the wheel, which largely radiates noise at frequencies close to its axial modes. Curve squeal has a deep random nature: small changes in operating conditions, e.g. friction coefficient, can lead to large variations in squeal occurrence and/or noise levels.

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Two mechanisms are thought to be at the origin of the squeal phenomenon: falling friction and mode coupling [1].

1.1 Stability analysis

The dynamic equilibrium of the wheel/rail system can be condensed at the contact degrees of freedom:

$$[Y_{nn}]\{f_n\} + [Y_{nt}]\{f_t\} = 0 \\ [Y_{nt}]\{f_n\} + [Y_{tt}]\{f_t\} = \{\Delta\dot{u}_t\} \quad (1)$$

where $[Y_{nn}]$, $[Y_{nt}]$ and $[Y_{tt}]$ are the total contact mobilities. Indexes n and t refer to normal and tangential directions respectively. $\{f_t\}$ and $\{f_n\}$ are friction and normal forces respectively. $\{\Delta\dot{u}_t\}$ is the instantaneous tangential velocity at the wheel/rail interface.

For small oscillations around the quasi-static equilibrium, the dynamic part of the friction force can be linearized. Finally, by assuming harmonic oscillations, a closed-loop equation for friction forces can be found:

$$\{f_t\} = [H]\{f_t\} \quad (2)$$

The stability analysis consists in the application of the Nyquist criterion to Eqn. (2). Details of the approach can be found in [2].

1.2 Sound power estimation

The stability analysis allows to predict the occurrence of the squeal phenomenon for a given set of input parameters (e.g. curve radius, wheel type, friction conditions, etc.). However, the stability analysis does not allow the prediction of the amplitudes of the non-linear self-sustained vibrations resulting from these instabilities (see Fig. 2). These amplitudes could be an objective indicator of the squeal noise severity.

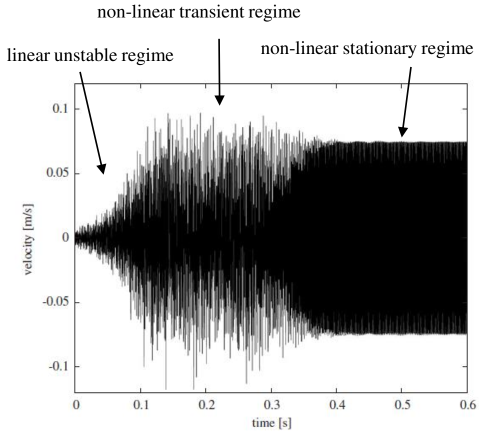

Figure 2: Typical time history of self-sustained vibrations [4].

The amplitudes and time evolution of nonlinear vibrations are most often calculated through numerical integration of the dynamic equations in the time domain. A disadvantage of this method is that the integration has to be carried out over a sufficiently long time interval for the transient regime to stabilize.

To circumvent this issue, a simplified method is used here, allowing a direct computation of the stationary regime, called 'limit cycle'. The method is based on a balance of the injected and dissipated power in the system, and assumes a mono-harmonic response of the structure at each unstable frequency of the system.

The sound power radiated by the wheel, which is the dominant sound source of curve squeal noise, is estimated through the same method as the one used in the TWINS model [3]. The approach has been fully presented in [4].

A graphical user interface has been developed, based on this theoretical model.

The current paper details the use of the simulation tool. Section 2 presents the tool and gives some insight on possible application cases, section 3 illustrates a squeal analysis compared to measurement results, section 4 includes a parametric study focusing on squeal noise mitigation.

2. PRESENTATION OF THE TOOL

The graphical user interface includes input and result tabs, see Fig. 3 to Fig. 5.

Input data necessary to define a 'squeal scenario' can be grouped in 5 families, see Fig. 3:

- **Wheel and rolling stock**: wheelbase, wheel load, wheel geometry (type, diameter) and wheel modal base
- **Rail and track**: rail mobility at contact point
- **Kinematic conditions**: curve radius, angle of attack, train speed, track gauge
- **Contact**: lateral position of contact point on wheel, contact angle
- **Friction**: static friction coefficient

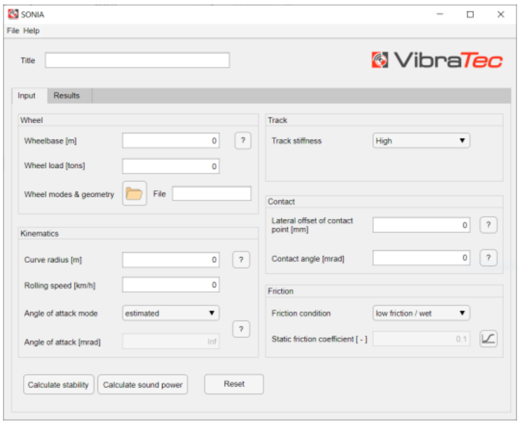

Figure 3. SONIA interface: input tab.

Input parameters can be defined based on simulations, analytical models, or measurements.

A common practice is to consider a range of estimated parameter values, instead of sets of deterministic values, and to perform a parametric analysis. This statistical approach is recommended when a large number of parameters is unknown (e.g. for the design of new railway lines). Besides, a parametric study is more appropriate for some families of input data whose identification, whether through simulation or measurements, can be demanding. This is typically the case for the angle of attack or the position of the contact point: their exact estimation would require multi-body simulations with a fine definition of the track geometry, or a heavy measurement campaign.

Outputs are provided for the two calculation steps: stability analysis (Fig. 4) and noise calculation (Fig. 5).

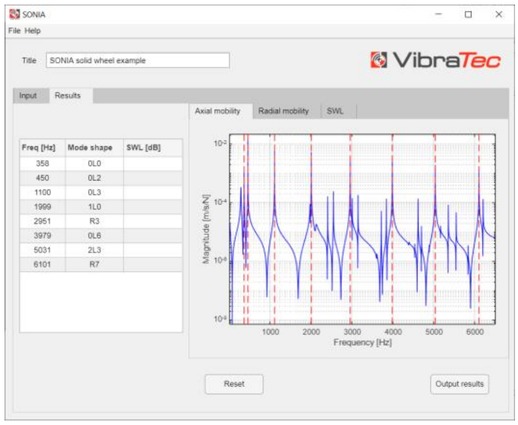

Figure 4. SONIA interface: outputs – stability.

The stability analysis allows to determine unstable frequencies of the system, which can be considered as 'squeal noise candidates'. In practice, a competition among squeal noise candidate modes happens, until one mode dominates and emerges in the total radiated noise [5].

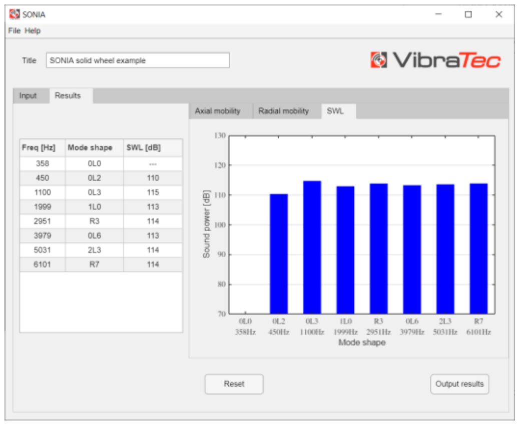

Figure 5. SONIA interface: outputs - sound power.

Squeal candidate frequencies are listed in a table and highlighted in the radial and axial mobility plots as red dashed lines, see Figure 4. Moreover, the table specifies the closest wheel mode to each instability. The measures for squeal reduction should focus on the wheel modes listed in the table.

SONIA takes into account both known mechanisms at the origin of curve squeal noise: falling friction and mode coupling.

The output of the noise calculation is the mono-harmonic sound power value for each instability found in the stability analysis: it is included in the updated left table, and displayed in a mono-harmonic sound power plot, see Figure 5. This should not be confused with a sound power spectrum. In practice, the sound power or pressure spectrum is generally dominated by one frequency (or mode). The sound power value of each predicted unstable frequency (or mode) in SONIA can be considered as an upper limit of the expected overall sound power in the real life system (conservative estimation).

SONIA has been validated against scientific literature. Two validation cases detailed in references [6] and [7] were reproduced with the tool and the same results as in the references were found.
In the following, the use of SONIA is quickly examined. Fig. 6 shows the results of a stability analysis for a determined curve scenario. Input data are omitted for the sake of conciseness.

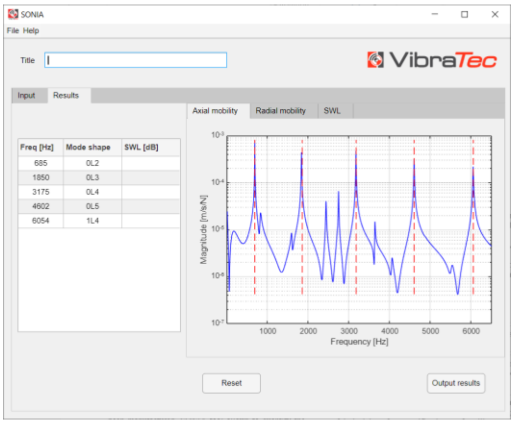

Figure 6. SONIA application – reference case.

Fig. 7 shows the results of the stability analysis for a case issued from the reference scenario, where the wheel damping is doubled for all wheel modes, thus simulating a wheel damper. The effect of increasing wheel damping is to reduce the number of instabilities (from 5 to 3). A further increase in damping would remove any instability. Hence, SONIA can be used to drive the wheel design, by estimating the minimum damping level required to prevent the risk of squeal for a certain curve configuration.

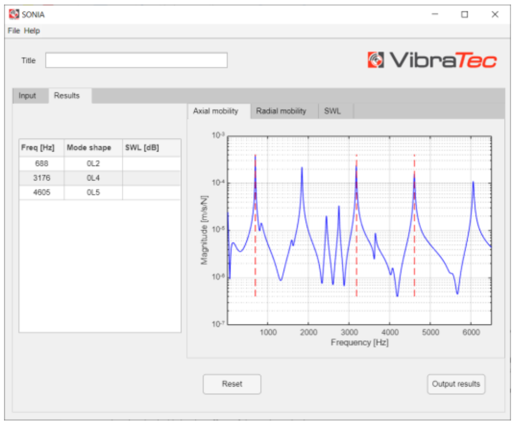

Figure 7. SONIA application – wheel damping.

Fig. 8 shows the results of the stability analysis for a case issued from the reference scenario, where the friction coefficient is halved, corresponding to lubrication of the wheel-rail interface. The effect of decreasing friction at the contact is to reduce the number of instabilities (from 5 to 4). Therefore, SONIA can be used to guide the choice of a lubrication or friction modifier product, by estimating the minimum friction coefficient preventing squeal occurrence.

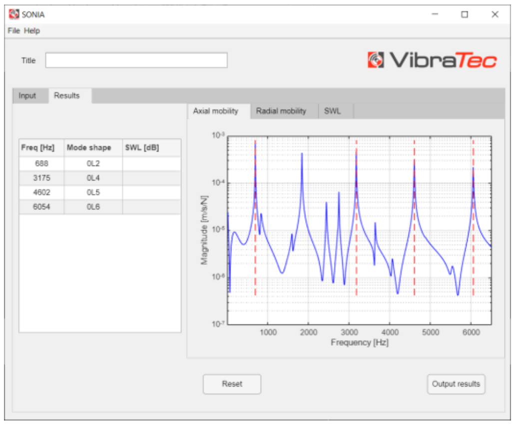

Figure 8. SONIA application – friction reduction.

3. APPLICATION CASE 1: SQUEAL SIMULATION OF A TRAMWAY

An example application presented in this section concerns a tramway network in France. Measurements (see Fig. 9) highlighted that squeal appears in some conditions (red curve in Fig. 9), and that the sound pressure spectrum is dominated by the 2 kHz and 5 kHz 1/3 octave bands: these correspond to the 0L3 and 0L5 axial wheel modes. In other conditions (black curve in Fig. 9) squeal is not present.

The curves in Fig. 9 are observed on the same track and rolling stock, and the difference between the measurements is related to weather conditions: in this case squeal did not occur while and immediately after rain.

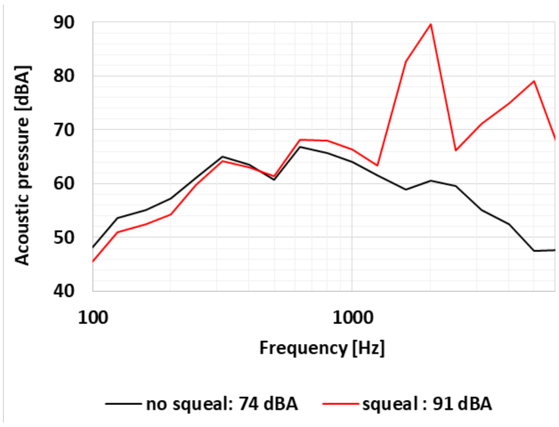

Figure 9. Tramway application: measurements.

Tab. 1 lists the parameters used for squeal noise simulations with SONIA, reproducing measurement conditions.

Table 1. Squeal calculation parameters

Wheel and rolling stock	Wheel load [tons]	4
	Wheelbase [m]	1.85
Kinematic parameters	Curve radius [m]	29
	Train speed [km/h]	15
	Angle of attack [mrad]	25
Track	Rail profile	Grooved, 41GPU
	Railpad vertical stiffness [MN/m]	800
	Railpad lateral stiffness [MN/m]	66
Contact	Lateral offset [mm]	7.5
	Contact angle [mrad]	24.8
Friction	Static friction coefficient [--]	0.5 / 0.1

The wheel model is tuned based on an experimental modal analysis.
The angle of attack, as well as contact parameters, are obtained through a multi-body calculation (Fig. 10).

The rail mobility is issued from an analytical calculation (Euler beam model), which is tuned to measured point mobilities.

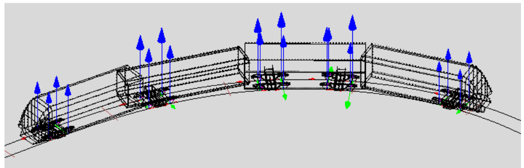

Figure 10: Tramway multi-body simulation model.

A static friction coefficient valued 0.5 is used to simulate dry contact conditions (squeal) [8], while the value 0.1 is relative to simulations in wet conditions (no squeal) [9, 10].

Fig. 11 and Fig. 12 show results of the simulation in dry and wet conditions, respectively. The results of the simulation in dry conditions (Fig. 11) highlight that wheel modes 0L2, 0L3, 0L4, 0L5 and 0L6 are candidates for squeal instabilities. This is coherent with measurements, where squeal noise peaks were observed at the frequencies of 0L3 and 0L5 wheel modes.

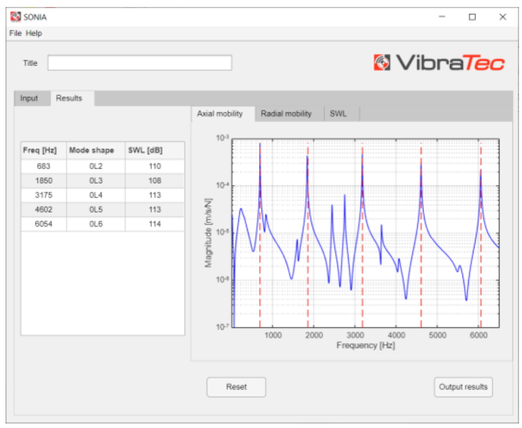

Figure 11. Tramway application: simulation - dry.

The sound power value handed by SONIA (108 dBA for modes 0L3 and 113 dBA for modes 0L5), is a conservative estimation. Experimental observations however showed a higher sound contribution of wheel mode 0L3 than the one of mode 0L5. The reason for this difference has not been investigated yet, and requires further work. It is possibly linked to the non-linear evolution of the system dynamics, but other causes cannot be excluded.

The simulation in wet conditions (Fig. 12) confirms that no squeal instabilities are experienced in this condition.

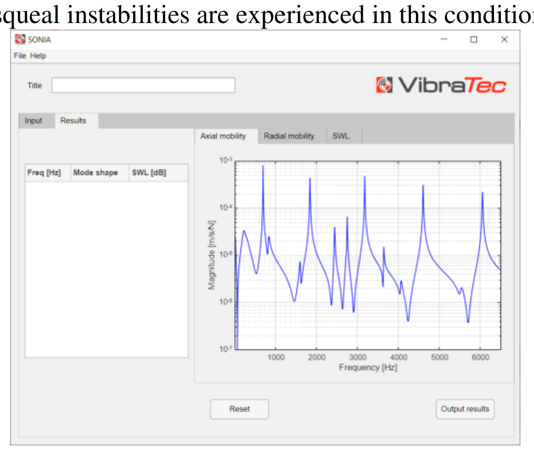

Figure 12. Tramway application: simulation - wet.

4. APPLICATION CASE 2: PARAMETRIC STUDY

A second application case is focused on squeal mitigation. For the application case 1 in the previous section, squeal mitigation could consist in increasing the damping of wheel modes 0L3 and 0L5 by using wheel dampers.
A set of wheel damper prototypes were manufactured by the wheel supplier, and their modal damping was measured in the laboratory. This modal damping was considered in the wheel model used in the SONIA tool. The analysis allows to quantify the effectiveness of this mitigation measure through simulation.
Fig. 13 shows the simulation results for the case with wheel damper prototypes based on the previous case in Figure 11.

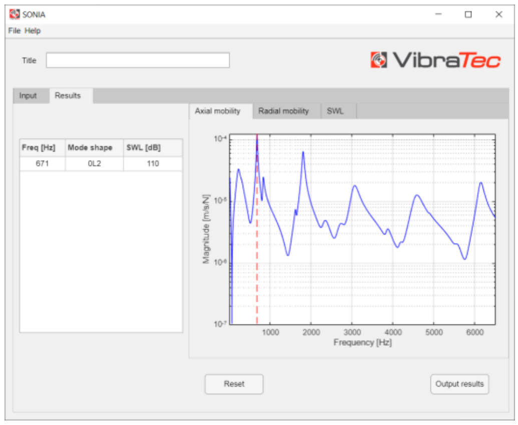

Figure 13. Tramway application: parametric study.

Thanks to the applied wheel damping, critical wheel modes 0L3 and 0L5 are no longer unstable, thus confirming that squeal could be suppressed by using the investigated wheel dampers.

5. CONCLUSIONS AND PERSPECTIVES

SONIA allows to evaluate the risk of curve squeal occurrence by identifying potential squeal candidates in terms of unstable frequencies. Furthermore, the tool is able to estimate conservatively the sound power radiated by the wheel for each unstable frequency.

The tool has been validated against cases from the scientific literature, and allows to reproduce experimental observations found in a tramway system.

Two example application cases were presented, where a tramway situation was considered: a qualitative comparison with measurements was performed, showing a good accordance with the simulation. Further analyses and comparisons, namely with other railway systems such as main lines or metros, will be carried out in order to confirm SONIA's applicability to these systems.

In its current state, SONIA is able to evaluate the risk of curve squeal noise, for example on new railway lines or linked to the introduction of new rolling stock on existing lines. It can also be used to design and test numerically, curve squeal noise mitigation solutions such as resilient wheels, wheel dampers and friction management.

Future works aim to improve the representativity of the friction model, to extend the squeal model to flange noise, and to include the mode competition phenomenon allowing a more precise prediction. In the end, further comparisons to measurement cases also allow to improve the SONIA tool.

6. REFERENCES

[1] D. J. Thompson, G. Squicciarini, B. Ding and L. Baeza, "A state-of-the-art review of curve squeal noise: phenomena, mechanisms, modelling and mitigation". *Noise and Vibration Mitigation for Rail Transportation Systems, Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, 139, pp.3–41 (2018).

[2] F. G. De Beer, M. H. A. Janssens and P. P. Kooijman, "Squeal noise of rail-bound vehicles influenced by lateral contact position". *Journal of Sound and Vibration*, 67, pp.497–507 (2003).

[3] M.H.A. Janssens, D. J. Thompson, F.G. de Beer, *TWINS version 3.4. Track-Wheel Interaction Noise Software. Theoretical Manual*. 2019.

[4] O. Chiello, R. Tufano and M. Rissmann, "Estimation of vibration limit cycles from wheel/rail mobilities for the prediction of curve squeal noise" in Proc. of the International Workshop on Railway Noise, (Shanghai, China), 2022.

[5] O. Chiello, J.-B. Ayasseb, N. Vincent and J.-R. Koch, "Curve squeal of urban rolling stock—Part 3: Theoretical model". *Journal of Sound and Vibration*, 293, pp.710–727 (2006).

[6] B. Ding, G. Squicciarini and D.J. Thompson, "Effect of rail dynamics on curve squeal under constant friction conditions". *Journal of Sound and Vibration*, 442, pp.183–199 (2019).

[7] B. Ding, G. Squicciarini, D.J. Thompson and R. Corradi, "An assessment of mode coupling and falling friction mechanisms in railway curve squeal through a simplified approach". *Journal of Sound and Vibration*, 423, pp.126–140 (2018).

[8] R. Stock, L. Stanlake, C. Hardwick, M. Yu, D. Eadie, and R. Lewis, "Material concepts for top of rail friction management – Classification, characterisation and application". *Wear*, 366–367: pp. 225–232 (2016).

[9] J. R. Koch, N. Vincent, H. Chollet, and O. Chiello, "Curve squeal of urban rolling stock—Part 2: Parametric study on a 1/4 scale test rig". *Journal of Sound and Vibration*, 293(3): pp. 701–709 (2006).

[10] W. Zhang, J. Chen, X. Wu, and X. Jin, "Wheel/rail adhesion and analysis by using full scale roller rig". *Wear*, 253(1): pp. 82–88 (2002).