Ballast Flying Risk Assessment Method for High Speed Line

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1. Introduction

With the development of High Speed Lines, another form of rail and rolling stock damage has become apparent, termed ballast flight. Indeed, ballast particles might become airborne during train passage and cause damages to both rail and rolling stocks. The different operators which observed the phenomenon of ballast projection under regular meteorological conditions have identified a need to increase the knowledge about this phenomenon and its consequences on railway infrastructure and vehicles. As for the assessment of the overturning risk caused by an intense cross wind gust, the phenomenon of ballast projection needs a risk evaluation approach because of its direct impact on the running of trains. The phenomenon of ballast projection and the assessment of the overturning risk caused by an intense cross wind gust are currently two subjects of risk evaluation because of the direct impact on the safety and the reliability of commercial railway operation. From previous investigations achieved during the DeuFraKo project “Aerodynamics in Open Air” [1] and different laboratory tests carried out in Korea, Japan [2,3], ballast flying mechanism has been linked to the intensity and gust duration and can be qualified of sporadic phenomenon.

The purpose of this article is to present a risk assessment method for ballast flying phenomenon which has been developed by taking into account flow field measurements on commercial speeds, numerical development of ballast motion under aerodynamic load using a discrete element approach and the Stress Strength Interference Analysis approach which allows to carry on risk analysis. A relevant parameter which describes the relation between ballast motion and flow field properties has been identified and a complete study has been done to evaluate the risk of ballast flying for different vehicles, commercial speeds or track conditions. The whole results can be applied to evaluate both the probability that the ballast flying phenomenon occurs and the consequences for railway maintenance. As a conclusion it is possible to propose an alternative to a GAME approach (Globalement Au Moins Equivalent, ie Globally At Least Equivalent method) by introducing a probability to reach a number of ejected grains threshold.

2. Framework

This part of the paper is a summary of the whole approach to evaluate ballast flying risk. The proposed framework is based on the following ideas:
- it is important to propose a parameter which links the aerodynamic properties of train and the ballast motion,
- the ballast flying risk is due to the combination of the presence of ballast grains on sleepers and air flow properties,
- the variability of all parameters is a key to handle ballast flying.

As a consequence, it is necessary to propose a method which can take into account variability and evaluate the risk: the proposed method is the Stress Strength Interference Analysis. The output of this method is a level of risk as a function of ballast initial position, the aerodynamic properties of a set of trains, and the quality of track to limit ballast motion.

In order to fulfill the whole step, we propose to use in situ measurements of flow fields and discrete element modelling to predict ballast motion.
2.1 Flow field properties

The flow field has been constructed from in situ measurements. The measurements have been acquired from the setup presented on Fig. 3 composed of a set of 20 Pitot tubes with a frame rate of 2400 Hz. This setup has been implemented on the track during commercial running of trains in order to have a statistical description of flow field. These choices have been motivated from the conclusions of the report of the Deufrako project AOA. [5].

2.2 Numerical simulations

The simulations were carried out by means of the contact dynamics (CD) method with irregular polyhedral particles. In this section we present the properties of this numerical method and compare it to a more classical numerical approach using molecular dynamics (MD) [1,2,3].

The aim of coupling aerodynamic loads on track and mechanical numerical computations is to characterize the motion of ballast grains over several different aerodynamic flows. The numerical modeling of the behavior of a collection of rigid bodies under the action of fluid is a tricky problem. The proposed approach is to consider the contribution of fluid as an external loading on grains, like the gravity field, then to solve the interaction problem between grains by Non Smooth Contact Dynamics approach. The aerodynamic flow can be described as field of speed vectors represented by a three-dimensional matrix defined by the space resolution corresponding to the average diameter of ballast grains for horizontal plan, 0,05 m, and 0,005 m for the vertical part.

A good correlation between ballast motion from experimental tests and numerical simulations has been noticed [11].

2.3 A relevant parameter of ballast flying

From the numerical simulations and in situ measurements, we have investigated several parameters which can describe the number of displaced grains during one train passage. The general idea is to propose a parameter which can be calculated from the characteristics of the flow field and to investigated for each measurement its correlation with the percentage of grains which have been moved over 10 cm.

The identified relevant parameter is the sum of signal power for the whole set of Pitot tubes:

$$P_{Tot} = \frac{1}{(t_2 - t_1)} \sum_{i=1}^{N} \int_{t_1}^{t_2} \| V(t) \|^2 \, dt$$
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From the numerical simulations coupling granular approach and fluid interaction, we can exhibit that a linear relation between $P_{tot}$ and the percentage of displaced grains can be a good approximation with a correlation 82% (Fig. 2).

2.4 Probability dense function of grains on sleepers

The ballast initial position on track is crucial for the ballast flying phenomenon. According to studies on this subject, having grains on sleepers is the worst configuration to try to limit the probability of having ballast flying.

The probability dense function if the density of grains on sleepers has been arbitrary chosen from practical point of view respects the following observation points:

- in most of cases, there is no grains on the sleepers,
- the presence of numerous grains in case of maintenance work is not often observed,

For these reasons, we propose an exponential law which gives the probability to have a density of grains on sleepers (Fig 3).
3. A general method

The Stress Strength Interference Analysis approach is an evaluation of the probabilistic interaction between two independent probability dense functions. This interference can be assumed as a failure probability for the considered problem. The general framework of the method is summarized on Fig. 4 [6,7].

The probability dense function of Stress $S_T$ and the pdf of Strength, $S_R$ are considered as normal Gaussian laws (Eq. 3):

$$S_T \in N(\mu, \sigma), S_R \in N(\mu, \sigma)$$

The failure probability of these pdf can be evaluated from the following formula:

$$P_f = \int_{0}^{\infty} f_{S_T}(x) F_{S_R}(x) dx \quad P_f = \int_{0}^{\infty} f_{S_T}(x) F_{S_R}(x) dx$$

with $f_{S_T}$ the probability dense function of Stress and $F_{S_R}$ the repartition function of Strength. If we consider that the two probability dense functions are Gaussian then we have the following analytic formula to calculate the failure probability by considering $Z = S_R - S_T$:

The standard deviation and the mean of the distribution can be written like (Eq. 5):

$$\mu_z = \mu_{S_R} - \mu_{S_T}, \sigma_z = \sigma_{S_R} - \sigma_{S_T}$$

Then the probability of failure is defined as (Eq. 6):

$$P_d = P(Z < 0) = P(\mu_z + U\sigma_z < 0) = P(U < \frac{\mu_z - \mu - S_R}{\sqrt{\sigma_{z}^2 + \sigma_{S_T}^2}})$$

Which can also be calculated by the following formula if $Z$ is a Gaussian distribution,

$$P_d = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(-\frac{x^2}{2}\right) dx$$

For the ballast flying phenomenon, we propose to characterize the Stress by the variability of the Signal Power and the Strength using the results of the numerical simulations.

In this study we need to propose a definition of Strength and Stress. These definitions are based on the relation between the number of ejected grains and the percentage of grains displaced over 10 cm longitudinally (Fig. 5).
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By fixing a threshold of ejected grains, we obtain the corresponding percentage and then, by using the relation described in Fig. 3 we get the mean of global signal power corresponding to the threshold we fixed. Its standard deviation is calculated using a projection of all the data on a threshold, following the linear relation.

To get the Stress definition and values, we consider a type of train, a range of speed circulation and we use the global signal power values to get a mean and standard deviation, verifying that the values are following a Gaussian normal law thanks to an adequation test.

4. Results

4.1 Adequation test for statistical law identification

The SSIA approach has been proposed for Gaussian laws. The first step of our investigation is to verify that the Global Signal power distribution for different trains (Fig. 6) verify this law by using Chi 2 test.
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<table>
<thead>
<tr>
<th>Signal Power value: mean and standard deviation</th>
<th>Train A</th>
<th>Train B</th>
<th>Train C</th>
<th>Train D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean / Standard Deviation</td>
<td>26100 / 585</td>
<td>26111 / 573</td>
<td>29170 / 544</td>
<td>28036 / 736</td>
</tr>
<tr>
<td>Chi2 test for normal law distribution (0.05%)</td>
<td>Accepted</td>
<td>Accepted</td>
<td>Accepted</td>
<td>Accepted</td>
</tr>
</tbody>
</table>

From the measurements and the evaluation of global signal power we find that for a Chi 2 test all data set follow the Gaussian law distribution.

4.2 Risk analysis

In this paragraph, we consider the train B, single unit for two specific commercial circulation speeds: 300 and 320 km/h.

![Figure 7: Pdf of global signal power - Train B](image)

From the Fig. 6 and adequation tests, we can conclude that the stress, i.e. pdf of signal power of train B at 300 and 320 km/h follows a Gaussian distribution law.

From this, we calculate the risk level for 5 and 15 ejected grains (Fig. 7).

<table>
<thead>
<tr>
<th>Stress</th>
<th>300 km/h</th>
<th>320 km/h</th>
<th>Strength</th>
<th>Ejected grains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk</td>
<td>22967 / 772</td>
<td>26000 / 1041</td>
<td>30544 / 1800</td>
<td>5</td>
</tr>
<tr>
<td>5.46E-05</td>
<td>1.44E-02</td>
<td>33848 / 1800</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

With the risk evaluation, we can see the levels of risk for a similar train circulating at different speeds are very different. The risk evaluation through the SSIA approach using the global signal power as a parameter is relevant.

5. Conclusion

The impact of ballast flying phenomenon on maintenance of track and/or of trains cannot be neglected. From the state of the art it is well known that the phenomenon is strongly dependent of the train type, the track and the running speed [5,8,10,11]. It is clearly a sporadic phenomenon which is difficult to predict or to characterize under real conditions.
In this paper we present a general approach which is based on measurements and numerical simulation. This first step shows that it is possible to find a relevant parameter linked to ballast flying: the global signal power of air speed signal.

This parameter and its variability allow to evaluate the risk level to have ejected grains for different trains. This parameter follows a normal Gaussian law which is required for applying the Stress Strength Analysis. The improvement of the numerical model by experimental results is needed to validate the relationship between global signal power and ballast motion under aerodynamic load.

The comparison between a G.A.M.E. approach by considering the mean air speed of the worst train and the risk approach shows that in the second case it is possible to discriminate the type of trains which have slight differences of mean air speed. These results show that for homologation or conception, the risk approach allows easily with one parameter and fixed variability to evaluate ballast flying risk.

The next step will be the in situ investigation by analysing grain motion on ballasted track under aerodynamic loads. This kind of tests will give a relation between air flow properties and ballast motion which is a crucial point for ballast flying phenomenon risk assessment.


