VIBRATION SENSING FOR RAILWAY DERAILMENT BASED ON NADAL’S AND SPERLING’S THEORY USING OMS

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ABSTRACT

Railways are large infrastructures and are the prime modes of transportation in many countries. As it is closely associated with passenger and cargo transportation, it owns high risk in terms of human lives and cost of assets. New technology and better safety standards are constantly introduced but accidents do occur. There will always be some risk associated with derailments but it can be reduced by elimination of the root causes. A derailment is an accident on a railway in which a train leaves the rails, which can result in damage, injury and death. In the case of a railway vehicle running on track, irregularities in track geometry can lead to complex dynamic interaction between the vehicle and track. The resulting dynamic forces accelerate the track deformation process and may lead to a derailment situation. Early detection of undesirable vehicle-track interaction allows for timely intervention before the situation presents a serious derailment risk. In this paper, it mainly focused on the ratio of vertical and lateral forces that tend to produce and those who oppose the derailment, must kept within certain limits. In some cases this system of forces is responsible of the boarding on track of the bandage rim and following the derailment of the axle. On the basis of these forces, decisions can be made about the levels of passenger comfort, and definitely, likelihood of derailments as a vehicle is run over the section of the track.

Keywords: derailment, rail, vertical, lateral, force, track, vibration sensing.

I. INTRODUCTION

The components of the process of rail transport are: railways, locomotive and wagons. The cost of rail accident has been always be large, especially in the case of passenger trains or trains carrying hazardous material. One of the most damaging rail accidents is a derailment. A derailment is an accident on a railway in which a train leaves the rails, which can result in damage injury, and death. The majority of derailment causes can be grouped into
three major categories: track related, equipment related and train operation-related. Detecting problems with the rail such as track buckling, broken rails and track geometry issues, before they cause an accident will improve the safety and reliability of rail transportation by preventing derailments due to track failure. This is a major source of worry since the old tracks may not be able to handle current high speed locomotives and may be a source of derailment. Rerailing a train after it has derailed is not an easy task, and often requires the use of large rail mounted cranes. Derailment of a train occurs when the wheels lift and slip out of the track. In more specific terms, a derailment occurs when the ratio of lateral displacement to vertical displacement, which is termed $L/V$, ratio-exceeds a critical limit whose value is typically 1.4\[1\]. One of the major type of derailment has been studied is Excessive speed derailment and the two different mechanism cause excessive speed derailment.

1) **Wheel flange climb**: in which the wheel is lifted off the track because the friction between the flange and the gauge face of the rail is too great, causing the wheel flange to climb outwards over the head of the rail. It generally occurs on curves. The wheel on the outer rail usually experiences a base level of lateral force to vertical force ratio.

2) **Rail roll**: in which the horizontal force applied by the flange to the gauge face of the rail is too great, overcoming the anchoring forces of rail spikes and clips.

These are two extreme conditions that result from excessive vehicle speed. The “$L/V$ ratio”, which is the ratio of the lateral to vertical forces on the rail, is a critical factor in manufacturing a safe speed.

### II. OBJECTIVE

With reference to this paper, the main objective is to avoid sudden damages or accidents causes by wheel climb and rail roll that leads to derailment. Since, not all the faults described in this paper, the priority given to the wheel flange climb and rail roll in which the wheel is lifted off the track due to track defect or broken rail. The study of the derailment has been focused about the defects in the train itself, but in this paper, it mainly focuses on the misaligned railroad track defect which implies track discontinuity, due to this the wheel lifts off the rail and therefore derailment can occur. The main purpose is to prevent derailment to monitor the causes related to it and identify the actions related to it. The type of derailment described above have a common cause of high lateral force at the wheel-rail interface. Therefore, any condition that leads to high lateral forces or lead to lower the ability of the system to sustain the force should be corrected. This is possible only when the vibration related to the forces should not cross the limit; otherwise the vibration that comes out due to broken rail is very high and can be computed using Simulation method to detect the level of derailment. The effect of vibration depends on the magnitude of acceleration suffered by a passenger, its direction and frequency. The paper studies safety of derailment by wheel flange climbing and the vibration comfort for a passenger. To meet this condition, velocity, acceleration or jerk of vibration of train must be limited to certain extent.

1) **Oscillation Monitoring System (OMS):**

OMS is a laptop based oscillation monitoring system used for track monitoring system used for track monitoring by measuring of the following parameters:

- Vertical and lateral acceleration on the loco/coach floor.
- Speed.
- Sperling ride index
OMS consists of the following parts:

The system is capable of measuring the accelerations in the bandwidth range of 0.4Hz to 20.0Hz. It comprises a memory buffer with storage capacity in the range of 2 to 8Kbytes. The system is capable of withstanding vibrations up to 1g in all three axes.

III. ANALYSIS AND RELATED WORK

The study and the analysis are totally based upon the criteria of safety against derailment. The various criteria can be applied in the assessment of the results of computer simulations but the most important are connected with the safety of the vehicle. The likelihood of derailment is affected by the vehicle suspension as well as the track condition, and assessment of derailment is not simple. The ratio of forces that tend to produce and who oppose the derailment must be kept within certain limits. In some cases this system of forces is responsible of the boarding on track of the bandage rim and following the derailment of the axle. Forces that appear are of two types [4].

1) Vertical force.
2) Horizontal force.

After the studies conducted by researchers as Nadal, Wagner, Heumann it has been found that the downwards vertical forces prevent derailing while the horizontal forces favour it [4]. In this paper, Nadal’s formula has been given priority for the safety against derailment as it concentrated on wheel flange climb due to steady force. In the normal running of a railway vehicle, the only point of contact with the rail is in the tread part of the wheel. The flange only contacts the rail if the curving performance of the vehicle is exceeded and the condition of derailment normally occurs and it is referred to as flange climbing [2]. As described above, flange climbing derailment is a process by which lateral forces acting on the wheel set cause one wheel to climb up and over the rail.

Fig 2: Force components at a wheel/rail contact
Where lateral (Y) and vertical (Q), normal force between the wheel and rail (N), lateral rolling-friction force (F), the cone angle of the force (λ) and, the coefficient of friction between wheel and rail (µ) [5].

Nadal expressions are [2]

\[
Y = N \sin \lambda - \mu N \cos \lambda \\
Q = N \cos \lambda - \mu N \sin \lambda
\]

The commonly used derailment quotient Y/Q can be calculated,

\[
Y/Q = \frac{(\tan \lambda - \mu)}{(1+\mu \tan \lambda)}
\]

This is called Nadal’s formula where the criteria of the safety against derailment is, Derailing forces < stabilising forces, i.e.[1] Y/Q should < (tan λ−µ)/ (1+µ tan λ).This is possible only when, Y is low, Q is high and µ is low. The formula thus indicates that for safety, λ should be large; its maximum value could be 90°. For a large majority of wheels, Nadal criterion admits that λ≈ 68° (for new wheel profile) and µ=0.25 and so it results:

\[
Y/Q ≤ 1.4 \quad [1]
\]

In other words, for safety against derailment, ratio Y/Q should not exceed 1.4. This is the threshold value. To allow for certain margin or factor of safety, a limiting value of 1.0 for ratio Y/Q has been laid down on the Indian Railways [1], as one of the criteria for assessment of rolling stock stability. The Nadal criterion is easy to implement and it is widely used for the assessment of the safety against derailment. In particular, this criterion is applied in a modified form in the UIC 518 code which is used for testing and approval of railway vehicle. The main modification adopted in the UIC 518 code is the requirement that the ratio Y/Q exceeds the assumed critical value of 0.8 over 2m track interval in 0.05 second and when such duration is less than 5 second then the value of Y/Q is (0.04/t) [1][5]. This is done because derailment of a vehicle can take place only if the ratio Y/Q exceeds the limit value for a sufficiently long time interval. These modifications of the Y/Q limit by increasing its value for short duration of the lateral force impulse have been proposed by Japanese National Railways (JNR). The occurrence of wheel climbing also strongly depends on the angle of attack (ψ of the wheel set described above). The present paper is basically based upon the comparative study in which the safety against derailment is assessed with the safe Nadal criterion modified according to the UIC Code 518[5][7]. In the first step of the safety analysis, the ratio Y/Q can be obtained from simulations is averaged at each track point over the surrounding 2m track section. Thus, the running average (Y/Q) on 2m will be calculated – it is done to satisfy the discussed requirement of minimum flange climb distance necessary for derailment. Further, as it is recommended in the UIC Code 518, the 99.85 percentile vale (Y/Q) on 2m|0.9985 is found. The obtained values (Y/Q) on 2m|0.9985 will be compared to the limit value 1.0 adopted by the Indian Railways [1]. On the basis of this comparison, it has been analysed that the value of (Y/Q) on 2m|0.9985 grows with the increase of the ride velocity but they do not exceed the limit value 1.0, and this can be favourable aspect to avoid derailment.

Furthermore the criterion of analysis of running safety is related with the ride comfort. The passenger ride comfort related to vibrations is of vital importance among a variety of other factors in comfort evaluation. The principle quantity that is relevant to the vibration aspect of the ride comfort is the acceleration that the passenger is subject to during the motion of a railway vehicle. The perception of the ride comfort depends on both amplitude and frequency
of the suffered acceleration as well as on its lateral and vertical direction. The below formula has been referred [11] for the passenger ride comfort value.

\[ N = 2 \sqrt{\frac{(a^{Wb})^2}{Y95} + \frac{(a^{Wc})^2}{Z95} + 4 \cdot \frac{(a^{Wd})^2}{ZP95} + 4 \cdot (a^{Wd}) \cdot (XD95)}{}} \]

Where, \( N \) is Ride comfort value (\( N \leq 1 \) very comfortable to \( N > 5 \) very uncomfortable).
\( a \) is Acceleration R.M.S. value over 5 sec.
\( Wb \) is Weighing filter for vertical acceleration.
\( Wc \) is Weighing filter for longitudinal acceleration.
\( Wd \) is Weighing filter for lateral acceleration.
\( X, Y, Z \) is Direction of measurement (longitudinal, lateral and vertical respectively.).
\( P, A, D \) is Position of measurement (floor, seat interface, backrest interface, respectively).
95 is 95th percentile of sampled 5s r.m.s- values under 5 min duration of constant and representative condition.

The above description shows that the frequency of the vibration depends on the vertical and lateral force. Therefore, the safe value of \( Y/Q \) should be matched with the cut-off frequency. It means that if \( Y/Q \) goes ahead of the value 1.0, the maximum vibration can be observed to monitor derailment.

IV. METHOD AND IMPLEMENTATION

![Flow chart](Fig 3: Work flow diagram)
1) Nadal’s Theory: The method that has been applied is based on the Nadal’s derailment criteria. After the studies conducted by Nadal, it has been found that the downwards vertical forces prevent derailing while the lateral forces favors it. Nadal’s formula has been given priority for the safety against derailment as it concentrated on wheel flange climb due to steady force.

![Fig 4: Force component at a wheel-rail contact.](image)

On resolving the forces along the flange angle, i.e.;
\[ Y \cos \lambda + \mu (Q \cos \lambda + Y \sin \lambda) < Q \sin \lambda \]
For safety against derailment,
Derailing forces < Stabilizing forces.
i.e. \[ Y/Q < (\tan \lambda - \mu) / (1+\mu \tan \lambda) \].
This is called Nadal’s Formula \[ \]. According to Indian Railways; For large majority of wheels, \( \lambda = 68^\circ \) (for new wheels) and \( \mu = 0.25 \).
Therefore, \( (\tan \lambda - \mu) / (1 + \mu \tan \lambda) \approx 1.4 \).

2) Vibration Sensing
Track irregularity, vehicle characteristics and vehicle generate motion quantities that are perceived by passengers. The combination of these quantities affects the passengers’ perception of ride quality and ride comfort as shown below:

![Fig 5: Significant track and Vehicle parameters for Ride Comfort](image)
Whole body vibration occurs when the body is supported on a surface which is vibrating. The vibration frequencies of interest vary according to the environment and the effects. The vibration between frequencies (0.4 Hz – 20 Hz) is the area of interest nowadays as it has much severe effects on human beings. The table shows the level of frequencies of vibration is given below:[16]

<table>
<thead>
<tr>
<th>Vibration Frequencies</th>
<th>Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 0.5 Hz</td>
<td>Symptoms of motion sickness, nausea.</td>
</tr>
<tr>
<td>Between 4 or 5 Hz</td>
<td>Interference of Hand Activities</td>
</tr>
<tr>
<td>Over 15 Hz</td>
<td>Vision is blurred</td>
</tr>
<tr>
<td>Between 10 or 20 Hz</td>
<td>Voice warble</td>
</tr>
</tbody>
</table>

In order to evaluate ride quality and ride comfort of a railroad, following equations has to be solved.

As the quality and ride comfort of a vehicle is assessed according to the effect of mechanical vibrations.

Ride Quality, $W_{z rq} = (a^3B^3)^{1/10}$.

Ride comfort, $W_{z rc} = (a^2B^2)^{1/6.67}$.

Where $a$, is a peak acceleration in cm/s², $f$ is frequency in Hz, $B$ is the acceleration weighing factor. The frequency weighing factors are defined for ride quality and ride comfort in different directions.

The weighing function $B$ for vehicle ride quality is

$$B = 1.14 \left[ (1 - 0.056 f^2) + (0.0645f(3.35 f^2))^2 \right]^{1/2}$$

$$\left[ (1 - 0.252 f^2 + (1.547 f - 0.0044f^3)^2 + (1+3.55 f^2) \right]$$

The weighing factor $B$ for ride comfort in the horizontal direction is

$$B_{w} = 0.737 \left[ \frac{1.911 f^2 + (0.25 f^2)^2}{(1 - 0.277 f^2 + (1.563 f - 0.0368 f^3)^2) \right]^{1/2}$$

The weighing factor $B$ for ride comfort in the vertical direction is

$$B_{s} = 0.588 \left[ \frac{1.911 f^2 + (0.25 f^2)^2}{(1 - 0.277 f^2 + (1.563 f - 0.0368 f^3)^2) \right]^{1/2}$$

The vehicle body vibration is not at a single frequency, and therefore the $W_{z}$ ride factor is determined for each individual frequency and it is calculated as;

$$W_{z total} = (W_{z1^{10}} + W_{z2^{10}} + + W_{z3^{10}} + W_{z4^{10}})^{1/10}.$$
An overview of the combination of Nadal’s theory and Sperling’s ride comfort value was given as introduction to the method that was implemented as part of the project.

Data sheet of the calculated values by dynamic frequency using Mat lab.

<table>
<thead>
<tr>
<th>S.N.</th>
<th>F</th>
<th>B</th>
<th>B_w</th>
<th>B_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0.4</td>
<td>0.74</td>
<td>0.358186</td>
<td>0.210614</td>
</tr>
<tr>
<td>2.</td>
<td>0.6</td>
<td>0.54</td>
<td>0.47508</td>
<td>0.279347</td>
</tr>
<tr>
<td>3.</td>
<td>0.8</td>
<td>0.38</td>
<td>0.556041</td>
<td>0.326952</td>
</tr>
<tr>
<td>4.</td>
<td>1</td>
<td>0.28</td>
<td>0.61307</td>
<td>0.360485</td>
</tr>
<tr>
<td>5.</td>
<td>5</td>
<td>1.75</td>
<td>1.01881</td>
<td>0.59906</td>
</tr>
<tr>
<td>6.</td>
<td>8</td>
<td>2.094</td>
<td>0.801344</td>
<td>0.47119</td>
</tr>
<tr>
<td>7.</td>
<td>10</td>
<td>2.32</td>
<td>0.617891</td>
<td>0.36332</td>
</tr>
<tr>
<td>8.</td>
<td>15</td>
<td>2.42</td>
<td>0.374592</td>
<td>0.22026</td>
</tr>
<tr>
<td>9.</td>
<td>18</td>
<td>2.48</td>
<td>0.302387</td>
<td>0.177804</td>
</tr>
<tr>
<td>10.</td>
<td>20</td>
<td>3.92</td>
<td>2.468176</td>
<td>2.157688</td>
</tr>
<tr>
<td>11.</td>
<td>26</td>
<td>4.76</td>
<td>2.500809</td>
<td>2.218076</td>
</tr>
<tr>
<td>12.</td>
<td>28</td>
<td>4.78</td>
<td>2.785429</td>
<td>2.509032</td>
</tr>
</tbody>
</table>

No.11 and no.12 are the Probability of accidents

Data sheet of the calculated values by static frequency using mat lab:

<table>
<thead>
<tr>
<th>F</th>
<th>Acceleration</th>
<th>λ</th>
<th>μ</th>
<th>W_{zq}</th>
<th>W_{zc}</th>
<th>Y/Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>68</td>
<td>0.25</td>
<td>0.018374</td>
<td>0.011809</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>68</td>
<td>0.25</td>
<td>0.0015</td>
<td>2.76E-05</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
<td>68</td>
<td>0.25</td>
<td>3.90E-04</td>
<td>3.65E-05</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>68</td>
<td>0.25</td>
<td>5086E-05</td>
<td>2.12E-06</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>68</td>
<td>0.25</td>
<td>-3.29E-06</td>
<td>-5020E-24</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>68</td>
<td>0.25</td>
<td>-1.35E-05</td>
<td>-4.34E-23</td>
<td>1.5</td>
</tr>
</tbody>
</table>

According to the rule, F=5 and F=6 are not acceptable for running.

The comparative values with respect to f, B, Acceleration and Y/Q are:

<table>
<thead>
<tr>
<th>Standard</th>
<th>F</th>
<th>B</th>
<th>B_w</th>
<th>B_s</th>
<th>Acceleration</th>
<th>Y/Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graph</td>
<td>1.5Hz</td>
<td>3.2</td>
<td>1.0</td>
<td>0.6</td>
<td>10</td>
<td>1.4</td>
</tr>
<tr>
<td>After</td>
<td>1.5Hz</td>
<td>2.42</td>
<td>0.4</td>
<td>0.2</td>
<td>10</td>
<td>1.3</td>
</tr>
</tbody>
</table>
RESULT AT GLANCE

1. On calculating the value of Y/Q, for both the forces we have the threshold values i.e. 1.4 and it should not exceed this value.
2. There is range of frequencies within a limit of 0.4 to 20 Hz. This has been taken as input to see the variations.
3. Applying the Sperling’s Ride index formula for both the lateral and vertical directions to maintain the ride comfort of the passengers.
4. On plotting the graph for the vibrations we could see the differences in safe and unsafe zone.

APPLICATIONS

1. It can better use in the Railway Department for the safety and security of passengers.
2. It can be used as an online sensor so as to predict the possibilities of accidents.
3. As the combination of Nadal’s and Sperling’s theories is applied, the comfort level of the passengers can be analyzed with the forces.
4. The L/V values can help in predicting the derailment accident as the best possible solution using the threshold values.

FUTURE ENHANCEMENT

Railway infrastructure is one of the fastest modes of transportation so it demands safety and security for their passengers. Therefore, Vibration sensing analysis is one of the major needs and requirement to monitor the condition the passengers. It is important to notice that when someone wants to travel through train, in our case, vibration sensing will most
likely to be checked. The ability of detecting the vibrations through a sensor and using that real data as an input is the most important thing to monitor the accidents. Further work can address the subjective experiments and prediction of accidents online using the above salient measures identified. Another possible avenue is to combine various fundamental metrics for better performance prediction.

REFERENCES