Intelligent control of wheel rail contact noise phenomenon in rail transportation

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Abstract. Railway transport systems play a very important role in the future of transport. They offer sustainable solutions that reduce carbon emissions (environmental requirements) and allow more mobility with better energy efficiency, and they generate advantageous economic benefits in the long term. But the interaction between the wheel and the rail is always very difficult to approach. There are a large number of studies in the literature on this problem. However, there is still no comprehensive approach. On this work we propose to study numerical modelling of contact between wheel-rail systems by using fuzzy logic. For this purpose, the experimental collection data reported in literature are used to predict the resonance noise during wheel-rail contact in rail transport. We found a good agreement between the elaborated model and the results of the literature.

1. Introduction

The contact between the Wheel and the rail is important for improving and facilitating the movement of the vehicle especially in bad conditions for better contact without noise, Skating…etc. Xiaojun. Hu et al. [1] did study experimentally and analyzed the sound field in the cavity of a rotating tire through a custom acoustic pressure sensor attached to the inner surface of the tire, to obtain the distribution and frequency characteristics of the sound field.

Continuous urbanization has resulted in a higher density of population in areas near railway tracks for many years. These factors raise the problem of train noise disruption, which is pushing infrastructure managers to systematically take measures to combat rail noise [2].

In the wheel/rail contact system in Sydney, Zhu. H et al. [3] have done an investigation and control to minimize degradation on mainly squat faults, they discover two types of white layer (Severe Deformation Induced White Etching Layer and Thermally Produced White Etching Layer). Also in Washington; Sound levels were assessed both near the track and at community locations near the subject maintenance yard. Outside the yard, the vibrations were almost undetectable; thus, squeal elimination. After about 3 months of service, however, a reduction of 14 dBA with some squeal was observed; and chronic squeal reappeared after 6 months of service. The rapid contact point wear of the facing treatment was due to this lack of effectiveness [4].

RailCorp. [5] revised the wheel squeal calculation, management and mitigation on the New South Wales Rail Network in 2004. Recent mitigation steps have centered on adding the head of the rail to a friction modifier. On some pages, this has been quite good, but it is now clear that on others it is only partially effective. A rolling touch test rig is used to investigate simple squeal behavior in order to validate wheel squeal prediction models. And, respectively, by experimental effect hammer analysis.
The lateral resonant frequencies and wheel mode shapes are calculated accordingly. Based on this, a dominant mode is defined as the primary peak in the squeal sound spectrum and is used as a measure of squeal incidence and magnitude. The lateral creep curves and wheel vibration amplitudes at different rolling speeds are measured and projected using a strain gauge technique. A simplified model is created involving the interaction of the dominant mode between lateral force and transverse vibration, and the experimental and simulated results show that the wheel's sound pressure level and vibration velocity increase significantly. The wheel squeal sound range has also been tested, they find that the cause of double peaks is due to wheel rotation and, as theoretically expected, the frequency divergence of double peaks increases with rolling [6].

Field measurements of wheel squeal events at a site in Australia in 2013 revealed a growing likelihood of a squeal event occurring as the relative humidity rises. A new method to calculate the lateral and normal force simultaneously on a test rig was created to check these effects, in order to evaluate the curves of friction-creep. The relative humidity within the acoustic enclosure of the test rig was changed under regulated conditions of 50 percent, 70 percent and 90 percent to investigate the influence of relative humidity on squeal and friction creep curves. The test rig results show that with the rise in relative humidity, the lateral adhesion ratio decreases marginally and that squeal is more likely in high relative humidity. The modeling analysis reveals that with the rise in relative humidity, the critical creep decreases, which means that negative damping occurs at a lower angle of attack [7].

Xiaogang L. [8] investigated the effect of various friction modifiers on the incidence of squeal on a rolling touch of the disk test rig under positive friction characteristics. In particular, under different rolling velocities and friction modifiers, friction-creep curves and squeal sound pressure levels were measured. The findings show that friction modifiers can remove or decrease the friction-creep curves' negative slope, but there is still squealing noise. A potential explanation why wheel squeal still persists after the application of friction modifiers is discovered by theoretical modeling of instant creep behaviors. Paul A. Meehan [9] demonstrated that the stiffness mode coupling induces a very high amplitude squeal outside the limits of the simplified creep model under only a limited range of contact angles and closely matched uncoupled modes. Only models of rail mass and damping are shown to reflect stiffness and viscous mode coupling occurrences, respectively, where the optimum amplitudes depend on the complex stiffness and rail damping, respectively. Excessive non-proportional damping and very high squeal amplitudes associated with reverse complete sliding are quantified and shown to be constrained by the reach of the effective analytical model. The analytical model is shown to provide insight into the effects of mode coupling dynamics on the amplitude of wheel squeal noise and can help explain the enigma that squeal tends to occur in the field unreliably [10].

The aim of this work is to develop a precise prediction model of the phenomenon of wheel-rail contact noise in rail transport using the fuzzy logic technique based on the experimental data from literature.

2. Experimental data
The data shown in Table 1 are the results of experimental tests done by Xiaojun Hu [1]. The objective of this study was to research the effects on frequencies of important process parameters (velocity, inflation pressure and the load).

| Test | Velocity (km/h) | Pressure (bar) | Load (N) | Frequency (Hz) |
|------|-----------------|---------------|---------|---------------|
| 1    | 40              | 2.5           | 3000    | 237           |
| 2    | 40              | 2.5           | 3500    | 237           |
| 3    | 40              | 2.5           | 4000    | 238           |
| 4    | 40              | 2.5           | 4500    | 239           |
| 5    | 40              | 2.2           | 3000    | 238           |
2.1. Fuzzy logic
Fuzzy logic is an extension of the Boolean logic that Lotfi Zadeh [11] developed in 1965 based on the mathematical theory of fuzzy sets, a generalization of classical set theory. By adding the idea of a degree of condition verification, thus making a condition of being in a state other than true or false, fuzzy logic offers a very significant versatility in the argument for use, which makes it possible to take into account inaccuracies and uncertainties. As a consequence, the principle of fuzzy logic applied to various manufacturing processes in which tests and expert expertise play an important role [11-12].

2.2. Fuzzy system
In this fuzzy system inference, we chose:
- three variables the input (Velocity, Inflation Pressure and the Load).
- one variable output (we have the Frequency).

|   |   |   |   |   |
|---|---|---|---|---|
| 6 | 40 | 2.2 | 3500 | 238 |
| 7 | 40 | 2.2 | 4000 | 237 |
| 8 | 40 | 2.2 | 4500 | 239 |
| 9 | 40 | 1.9 | 3000 | 237 |
|10 | 40 | 1.9 | 3500 | 238 |
|11 | 40 | 1.9 | 4000 | 239 |
|12 | 40 | 1.9 | 4500 | 239 |
|13 | 50 | 2.5 | 3000 | 235 |
|14 | 50 | 2.5 | 3500 | 235 |
|15 | 50 | 2.5 | 4000 | 235 |
|16 | 50 | 2.5 | 4500 | 237 |
|17 | 50 | 2.2 | 3000 | 236 |
|18 | 50 | 2.2 | 3500 | 236 |
|19 | 50 | 2.2 | 4000 | 236 |
|20 | 50 | 2.2 | 4500 | 236 |
|21 | 50 | 1.9 | 3000 | 236 |
|22 | 50 | 1.9 | 3500 | 237 |
|23 | 50 | 1.9 | 4000 | 237 |
|24 | 50 | 1.9 | 4500 | 237 |
|25 | 60 | 2.5 | 3000 | 237 |
|26 | 60 | 2.5 | 3500 | 237 |
|27 | 60 | 2.5 | 4000 | 238 |
|28 | 60 | 2.5 | 4500 | 237 |
|29 | 60 | 2.2 | 3000 | 237 |
|30 | 60 | 2.2 | 3500 | 237 |
|31 | 60 | 2.2 | 4000 | 238 |
|32 | 60 | 2.2 | 4500 | 238 |
|33 | 60 | 1.9 | 3000 | 237 |
|34 | 60 | 1.9 | 3500 | 238 |
|35 | 60 | 1.9 | 4000 | 238 |
|36 | 60 | 1.9 | 4500 | 238 |
Figure 1. Inputs and outputs of the fuzzy system.

Table 2. Input and output parameters for membership function.

| Factor    | Symbol | Unit      | Very Low (VL) | Low (L) | Medium (M) | High (H) | Very High (VH) |
|-----------|--------|-----------|---------------|---------|------------|----------|----------------|
| Velocity  | V      | Km/h      | -             | 40      | 50         | 60       | -              |
| Pressure  | Pa     | Bar       | -             | 1.9     | 2.2        | 2.5      | -              |
| Load      | P      | N         | -             | 3000    | 3500       | 4000     | 4500           |
| Frequency | fr     | Hz        | 235           | 236     | 237        | 238      | 239            |

Membership functions come in many forms figure 2, figure 3, figure 4, figure 5. In this study, triangular membership functions for the input variables in figure 6, figure 7, figure 8 and figure 10, explained in Table 2 and the figure 9 for output variables.
In order to properly define the linguistic variables for the outputs we have used the scatter plot in figure 9, which presents the distribution of the values of the frequency.
2.3. Fuzzy rules

The rule to calculate it’s come and represent Table 3:

If a velocity is… and Pressure is… and load is… so Frequency is…

| Table 3. Fuzzy rules. |
|-----------------------|
| Test | Velocity (km/h) | Pressure (bar) | Load (N) | Frequency (Hz) |
|------|-----------------|----------------|---------|-----------------|
| 1    | L               | H              | L       | M               |
| 2    | L               | H              | M       | M               |
| 3    | L               | H              | H       | H               |
| 4    | L               | H              | VH      | VH              |
2.4. Defuzzification

The difference between the observed and the forecasted value was determined by calculating the error. The (1) equation can be used to measure errors. A division of the absolute difference in the measurement value was accomplished by dividing the percentage of individual errors.

\[ e_t = \left( 1 - \frac{|f_{rx} - f_{rp}|}{f_{rx}} \right) \times 100\% \] (1)

Precision is determined using the expected value method to the observed value. The consistency of the model is \( A \) in equation (2), and \( N \) is the cumulative number of evaluated data sets. The model's precision is average individual precision.

\[ A = \frac{1}{N} \sum \left( 1 - \frac{|f_{rx} - f_{rp}|}{f_{rx}} \right) \times 100\% \] (2)

|   | L  | M  | L  | H  |
|---|----|----|----|----|
| 5 |    |    |    |    |
| 6 | L  | M  | M  | H  |
| 7 | L  | M  | H  | M  |
| 8 | L  | M  | VH | VH |
| 9 | L  | L  | L  | M  |
| 10| L  | L  | M  | H  |
| 11| L  | L  | H  | VH |
| 12| L  | L  | VH | VH |
| 13| M  | H  | L  | VL |
| 14| M  | H  | M  | VL |
| 15| M  | H  | H  | VL |
| 16| M  | H  | VH | M  |
| 17| M  | M  | L  | L  |
| 18| M  | M  | M  | L  |
| 19| M  | M  | H  | L  |
| 20| M  | M  | VH | L  |
| 21| M  | L  | L  | L  |
| 22| M  | L  | M  | M  |
| 23| M  | L  | H  | M  |
| 24| M  | L  | VH | M  |
| 25| H  | H  | L  | M  |
| 26| H  | H  | H  | M  |
| 27| H  | H  | H  | H  |
| 28| H  | H  | VH | M  |
| 29| H  | M  | L  | M  |
| 30| H  | M  | M  | M  |
| 31| H  | M  | H  | H  |
| 32| H  | M  | VH | H  |
| 33| H  | L  | L  | M  |
| 34| H  | L  | M  | M  |
| 35| H  | L  | H  | H  |
| 36| H  | L  | VH | H  |
3. Results
After using the fuzzy system and the rules of table 3 by equation 1, 2, we obtained the results presented in Table 4.

Table 4. Fuzzy results for calculate $E_i\%$ and $A\%$.

| Test | Frequency (Hz) | Frequency (Hz) | $E_i\%$ | $A\%$ |
|------|----------------|----------------|---------|--------|
| 1    | 237            | 237            | 0       | 100    |
| 2    | 237            | 237            | 0       | 100    |
| 3    | 238            | 238            | 0       | 100    |
| 4    | 239            | 239            | 0       | 100    |
| 5    | 238            | 238            | 0       | 100    |
| 6    | 238            | 238            | 0       | 100    |
| 7    | 237            | 237            | 0       | 100    |
| 8    | 239            | 239            | 0       | 100    |
| 9    | 237            | 237            | 0       | 100    |
| 10   | 238            | 238            | 0       | 100    |
| 11   | 239            | 239            | 0       | 100    |
| 12   | 239            | 239            | 0       | 100    |
| 13   | 235            | 235            | 0       | 100    |
| 14   | 235            | 235            | 0       | 100    |
| 15   | 235            | 235            | 0       | 100    |
| 16   | 237            | 237            | 0       | 100    |
| 17   | 236            | 236            | 0       | 100    |
| 18   | 236            | 236            | 0       | 100    |
| 19   | 236            | 236            | 0       | 100    |
| 20   | 236            | 236            | 0       | 100    |
| 21   | 236            | 236            | 0       | 100    |
| 22   | 237            | 237            | 0       | 100    |
| 23   | 237            | 237            | 0       | 100    |
| 24   | 237            | 237            | 0       | 100    |
| 25   | 237            | 237            | 0       | 100    |
| 26   | 237            | 237            | 0       | 100    |
| 27   | 238            | 238            | 0       | 100    |
| 28   | 237            | 237            | 0       | 100    |
| 29   | 237            | 237            | 0       | 100    |
| 30   | 237            | 237            | 0       | 100    |
| 31   | 238            | 238            | 0       | 100    |
| 32   | 238            | 238            | 0       | 100    |
| 33   | 237            | 237            | 0       | 100    |
| 34   | 238            | 238            | 0       | 100    |
| 35   | 238            | 238            | 0       | 100    |
| 36   | 238            | 238            | 0       | 100    |

$A = 100\%$
3.1 Schematic representation of the results
The figures below show the variation of the frequency as a function of the speed and of the load applied during the contact between wheel-rail.

Figure 11 shows the variation of the frequency depending on the speed and pressure.

![Figure 11. Variation of frequency with speed and pressure.](image)

Figure 12 shows the variation of the frequency depending on the speed and the load.

![Figure 12. Variation of frequency with speed and pressure.](image)

Both figures show that the maximum frequency Value is obtained for the maximum values of speed and load or pressure.

These figures allowed us to detect the noise zone as a function of the speed and pressure load applied during the contact between the wheel and the rail.

The fuzzy logic method helps us to optimize the input parameters in order to find good solutions for such a phenomenon.
3.2 Validation of results

The following figure shows the comparison between the values predicted by our model proposed by fuzzy logic and the values obtained from the literature.

![Comparison between the experimental result and fuzzy system result](image)

**Figure 13.** Comparison between the experimental result [1] and fuzzy system result.

From the figure 13, the curves are similar so our fuzzy logic based prediction model works well and with high accuracy and can be used as a solution to predict the wheel rail contact noise phenomenon in rail transportation.

4. Conclusion

The noise resulting from contact between wheel and rail to rail transport has a major effect on the health of train drivers and people. The work in this modest research, are part of the objective of the study and development of optimization techniques.

To validate our model developed by the fuzzy logic method proposed to study the wheel rail contact noise phenomenon in rail transportation, a comparison with the experimental study carried out by Xiaojun Hu study [1] was made.

The study we presented allowed us to conclude that

- The comparison and validation of the predicted results with the results of the experimental tests confirmed the accuracy of the models developed.
- The maximum values of the frequency are obtained for maximum values of speed and load or pressure.
- The fuzzy logic method is more reliable with an average error of 0 % and the precision of the developed model is 100 %.
- The fuzzy modeling technique could be an economical and efficient method to predict the wheel rail contact noise phenomenon in rail transportation.

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