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Generation of Realistic Artificial Track Irregularities for Multibody Simulation using Measured Geometric Data – from Mid-Chord to Space-Curve

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Abstract

The inclusion of geometric irregularities in railway simulations is essential since these track imperfections directly interfere with the vehicle’s dynamics. Since railways are constantly monitored by a control car, responsible for measuring irregularities and collecting information from the track, an option for railway simulations would be to use these measurements as an irregularity input in the software. The factor that makes this alternative impossible is that multibody simulation software only accepts irregularities in space-curve coordinates, while most measurements made track measurement car are using a mid-chord coordinate system. This paper presents a machine learning model to transform the railway irregularities measured from the mid-cord into space-curve. The transformed data is represented as a power spectrum density (PSD) function, to be used in the multibody simulation software SIMPACK. The best model was an Artificial Neural Network (ANN) with a R^2 coefficient of 0.9444 for vertical track irregularity and 0.8982 for horizontal track irregularity. For validation of the created PSD, results show the dynamic behaviour of a freight vehicle built in the SIMPACK in a real track fragment. The use of Wavelet Coherence showed a high correlation of around 0.95, confirming the correlation between the signal from simulations that used track irregularities generated by the PSD and the signal generated by simulations performed with the measured irregularities in space-curve.

Keywords: Heavy haul railway, Track irregularities, Machine Learning, Multibody simulation, Power Spectral Density (PSD), Artificial Neural Network.

1 Introduction

The inclusion of track irregularities in railway simulation is extremely important for the study of system dynamics since it involves the railway vehicle's running safety, ride comfort, and stability [1-5]. There are mainly two ways to include track irregularities in simulations like the ones performed by most of the commercial software. The first is based on the usage of artificial track irregularities generated by standards that describe their frequency spectrum as a Power Spectrum Density (PSD) function. The second approach uses measured irregularities, obtained from a track measurement car. The collected data can be in a chord-based system or an inertial-based system.

Comparing the two methods, chord-based measurements do not preserve the actual amplitude and phase of the irregularities while the inertial-based system does [6-7]. Due to this characteristic, chord-based systems are less accurate than the inertial-based system; however, their simplicity makes it the most used method for measuring such track characteristics. Because of these inaccuracies and internal configuration, multibody simulation software doesn't accept track irregularities measured in chord coordinates; only in inertial coordinates, also known as space-curve (SC). With a large number of chord-based measurements readily available and the need for realistic and precise multibody simulation, the conversion of chord-based measurements to SC is very important, especially when no inertial measurement data is available.

The purpose of this study is to convert the measured irregularities from a chord-based coordinate system to SC. The data generated from the applied model was used to create a PSD function that describes the railway's track condition and allows the generation of artificial track irregularities for more accurate multibody simulation. This also allows the simulation of long track segments without needing any more measured track irregularity data.

Since a mathematical function capable of converting chord-based coordinates to SC does not exist, machine learning was used due to its capacity of modelling highly nonlinear relationships with data [6-8]. This mapping between coordinate systems is a supervised learning problem and Artificial Neural Networks (ANN) were applied to solve it. From the output of the ANN, the PSD functions were created for both lateral and vertical track irregularities.

2 Methods

Figure 1 shows the flowchart of the methodology adopted in this paper. From track irregularity data provided by a Brazilian railway company, the first step is preprocessing the data, which involves converting the coordinates of the track irregularities from the chord-based system to SC. The second step is exploratory data analysis (EDA). This step is used to visualize the data and their distributions, check for anomalies, and study the correlation between variables to better understand the problem. The third step involves creating variables that help improve the mapping between the input and output variable, also known as feature engineering. Several statistical metrics in the time/space, frequency domains and polynomial variables will be created.

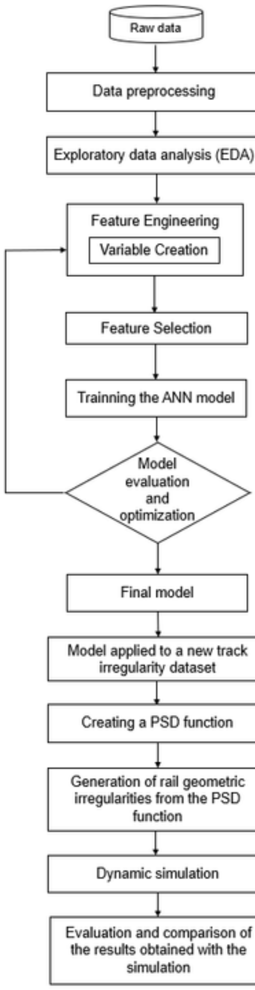

Figure 1: Methodology flowchart.

The feature engineering step led to the creation of a very large number of variables that must be minimized to avoid overfitting and large computational time. This leads to the fourth step which is feature selection. After this step, an Artificial Neural Network (ANN) was trained, evaluated, and optimized in an iterative process with the feature engineering and feature selection step. Following the optimization process, the final model was tested and evaluated on a new track irregularity dataset to verify the accuracy and the generalization of the network.

The trained ANN was applied to this new dataset, obtaining the track irregularities in SC. Welch's method was applied to the model's output with a Hanning window and 80% overlap to create the PSD function that describes the measured track irregularities.

In order to validate the created PSD, it is necessary to perform two simulations that compare the dynamic response obtained by using SC irregularities and the irregularities generated from the PSD function. This step is performed by using a GDE wagon with two Ride Control bogies modelled in the SIMPACK multibody dynamic software, running on the track model created from real geometric parameters of a track section from Brazil. The total length of the track is 782.98 m. It is composed of three tangents and two left-hand curves with a TR68 rail profile.

3 Results

The ANN was capable of converting measured track irregularities from the chord coordinate system to SC. A coefficient of determination (R^2) of 0.9444 was obtained for vertical track irregularity and 0.8982 for horizontal track irregularity, both for the right side. From the SC data, a PSD function was created to represent this signal for the vertical and horizontal irregularities, on the right and left sides of the track.

Figure 2 presents a comparison between the irregularities in SC and the irregularities generated from the PSD. Because this generation is a stochastic process, the irregularities are not equal but have similar spectral characteristics and amplitudes [9].

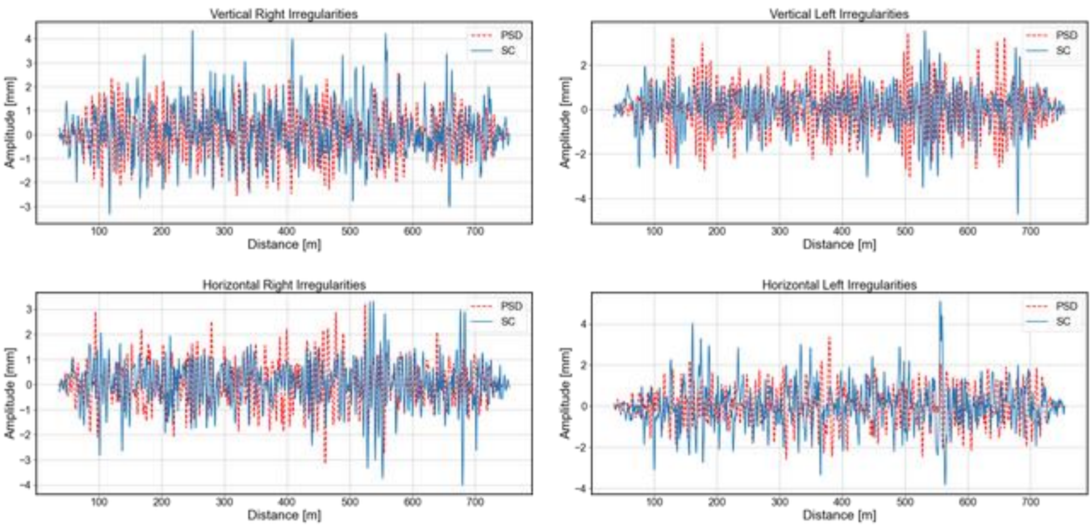

Figure 2: Comparison between the target track irregularity and the one created from the PSD.

Figure 3 shows the results for the vertical and lateral forces for the right wheel of the first wheelset. The wheel was selected because it has the largest force values due to the track's macrogeometry. As expected, the force values are not exactly the same but are very similar.

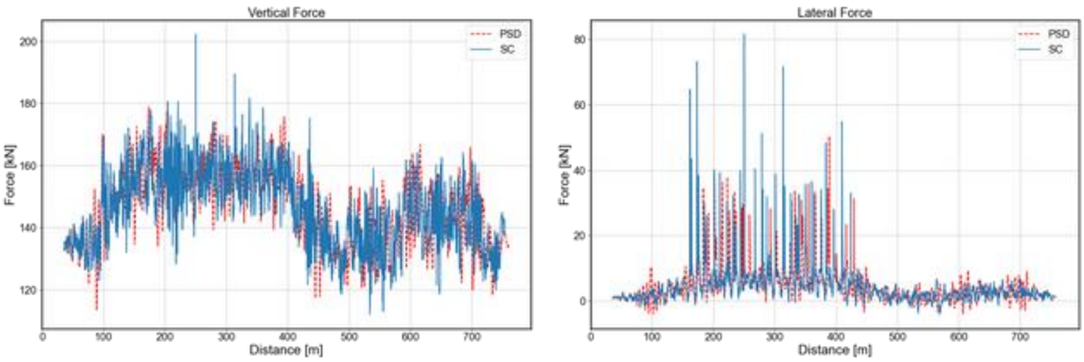

Figure 3: Comparison between the vertical and lateral forces generated in the simulations.

Wavelet transform was used to detect the correlation between the force signals generated from the simulation with the irregularities of both origins (PSD and SC) with the wavelet coherence coefficient. This coefficient exhibits an absolute value between 0 and 1, where the closer the coefficient is to 1, the greater the correlation between the signals [10].

Figure 4 shows the wavelet coherence for the vertical and lateral forces. There is a high correlation of around 0.95 in the wavelength range between 0.0 m^{-1} and 0.125 m^{-1}. Between 0.125 m^{-1} and 0.5 m^{-1}, blue patches of low correlation start to appear, being more prominent in the lateral force signal. This lower correlation for the lateral force signal could be due to the ANN's lower R^2 score when compared to the vertical track PSD. Above 0.5 m^{-1}, most of the force signals have low correlation with each other.

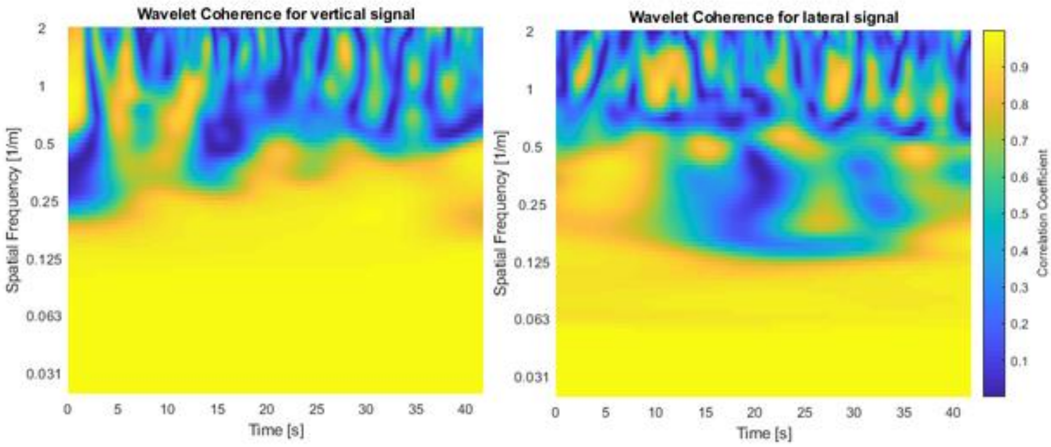

Figure 4: Wavelet Coherence for the force signals.

This result can be better understood by visualizing the Fast Fourier Transform (FFT) of the force signals, as shown in figure 5. Since most of the signal's energy is between 0.0 m^{-1} and 0.5 m^{-1}, bad correlations outside this range are not as relevant because of their low energy content.

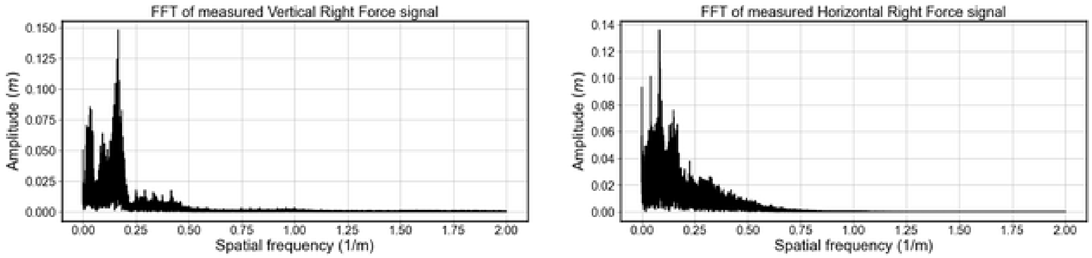

Figure 5: FFT applied to the original signal of measured irregularities.

4 Conclusions and Contributions

This paper proposes a methodology for generating realistic artificial track irregularities for multibody simulation by using measured track geometry data. This data was provided by a Brazilian railway company in a chord-coordinate system, which is the most common and simple representation. This type of representation has disadvantages since it does not preserve the signal's amplitude or phase. For this reason, multibody simulation software like SIMPACK does not accept track data in the chord system, but in an inertial reference system. To train a machine learning model capable of converting track irregularity coordinates, the raw data underwent preprocessing, feature engineering, and then feature selection.

An Artificial Neural Network (ANN) was trained and used to map the chord coordinate system to SC due to its capability of modelling highly nonlinear relationships. The ANN's output was used to create a Power Density Function (PSD) that represents the track's geometric condition.

Machine Learning algorithm was proposed as a quick and efficient solution to the problem of converting the reference system used in the measurement of railway irregularities. In this way, it is possible to insert these irregularities in multibody simulation software, obtaining results that are more similar to the real system. In addition, in order to circumvent a common problem that is a small amount of measured irregularity data, the study suggested the creation of a PSD function capable of representing these irregularities as a way of performing simulations with long stretches of track.

A R^2 coefficient of 0.9444 was obtained for vertical track irregularity and 0.8982 for horizontal track irregularity.

The methodology used to create the PSD function was validated from force results provided by a dynamic simulation in the SIMPACK software. Wavelet coherence was used to quantify the similarity between the two signals: a value close to 0.95, at the wavelength of the original measured irregularities (0.0 m^{-1} and 0.5 m^{-1}), was obtained for both the vertical and lateral force response similar dynamic responses. For the lateral signal, between wavelengths from 0.125 m^{-1} to 0.5 m^{-1}, points of lower correlation occur, which is explained by the lower coefficient of R^2 obtained in comparison to the vertical signal.

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