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A hybrid multi-objective imperialist competitive algorithm and Monte Carlo method for robust safety design of a rail vehicle

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This paper deals with the robust safety design optimization of a rail vehicle system moving in short radius curved tracks. A combined multi-objective imperialist competitive algorithm and Monte Carlo method is developed and used for the robust multi-objective optimization of the rail vehicle system. This robust optimization of rail vehicle safety considers simultaneously the derailment angle and its standard deviation where the design parameters uncertainties are considered. The obtained results showed that the robust design reduces significantly the sensitivity of the rail vehicle safety to the design parameters uncertainties compared to the determinist one and to the literature results.

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1. Introduction

It is a common practice in a rail vehicle (RV) safety design to consider the nominal values only as input variables for design optimization. Nejlaoui et al. [1] took care of the RV security in quasi-static cases by using the Genetic Algorithm (GA) method. He and McPhee [2] treated a mono-objective optimization design of the RV derailment by using Genetic Algorithms. The objective function is a weighted combination of the angle of attack and of the ratio of the lateral force to the vertical force applied by each wheel on the rail. To evaluate the RV safety system, Eom and Lee [3] developed a sensitivity analysis of the parameters related to the derailment coefficients of track conditions. Banerjee et al. [4] used a model with 18 degrees of freedom to analyze the RV safety through determining the critical speed.

However, the RV design parameters (DPs) have usually an uncertainty around their nominal values due to the presence of variations in manufacturing, geometry, and material properties. To estimate the effect of DP uncertainty on the performance of a mechanical system, several methods have been described. In particular, the Monte Carlo Simulation (MCS) is a popular tool because of its relative precision and simplicity [5]. Araujo et al. [6] use the MCS method to estimate the uncertainty of surface emissivity, obtained by dual spectral infrared radiometry at ambient temperature. Motevalli et al. [7] applied a MCS approach to study the water inflow uncertainty impact on the performance of both single and multi-reservoir systems.

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Nomenclature

i	Index of wheelset	y_{ki}	Transversal displacement of the wheelset i of bogie k
j	Index of wheel.	y_k	Transversal displacement of the bogie k
k	Index of bogie	$\bar{y}$	Transversal displacement of the car body
g	The gravity constant	α_{ki}	Yaw angle of the wheelset i of the bogie k
G_{ki}	Wheelset center of mass	α_k	Yaw angle of the bogie k
G_k	Bogie center of mass	$\bar{\alpha}$	Yaw angle of the car body
$\bar{G}$	Car body center of mass	θ_k	Roll angle of the bogie k
m	Half wheelset mass	$\bar{\theta}$	Roll angle of the car body
$\hat{m}$	Bearing box body mass	θ_{ki}	Roll angle of the wheelsets ki
M	Bogie mass	V	The speed of the vehicle
$\bar{M}$	Car body mass	K_u	Spring stiffness of the primary suspension in the direction u $(u = x, y, z)$
N	Normal load by a wheel	$\bar{K}_u$	Spring stiffness of the secondary suspension in the direction u
H	Vertical distance between the primary and the secondary suspension	d	Transversal distance between the primary suspension and G_k
h_0	Vertical distance between the primary suspension and G_k	$\bar{d}$	Transversal distance between the secondary suspension and the car body center of mass
δ	The rail inclination	R	Curvature radius of the wheel profile
γ_0	Inclination of the tangent plan of contact wheel–rail with the horizontal	R'	Curvature radius of the rail profile
e_0	Half spacing of the track	S	the normal force on the flange
γ_e	Equivalent conicity		
R_c	Radius of curve		

Other works have studied the robust product design where uncertainties of the DP are considered. Cheng and Li [8] have developed a hybrid differential evolution and sequential quadratic programming method that ensures robust mechanical structures under uncertain DP. Kalantari et al. [9] have developed a hybrid robust evolutionary algorithm by combining the NSGAII process with a local search method. This strategy is used to optimize composite structures under an uncertain fiber angle and a lamina thickness. Bouazizi et al. [10] studied the robust optimization of a vibration absorber using the GA. The robustness, defined by the ratio of the mean value to the standard deviation, is treated as an objective function.

This paper deals with the multi-objective robust design optimization of a rail vehicle moving in short-radius curved tracks based on the safety criteria. A combined algorithm based on the Multi-objective Imperialist Competitive Algorithm (MOICA) and the MCS is proposed. The obtained results are compared to literature ones. In section 2, the dynamic model of the RV is reviewed and the safety criterion is defined. Section 3 deals with the determinist multi-objective design optimization of RV safety. Then, the authors show that the determinist optimal solutions can be seriously altered by DP uncertainties. In Section 4, a novel algorithm is developed and used in multi-objective robust optimization. The results are discussed and compared with literature results. Finally, some concluding remarks are presented in section 5.

2. Model of the RV system

The RV system is made of a rigid car body C, bogies C_k and wheelsets S_{ki}. The connection between these components is represented by the secondary and the primary suspensions. Each suspension is formed by a system of linear springs and dampers, which work in three directions (Fig. 1) [1,11].

The longitudinal symmetry of the RV system leads to the decoupling of lateral, vertical and longitudinal motions [1,11]. In this paper, we focus on the lateral dynamic behavior of the RV system. To simplify the analysis without reducing the accuracy of the model, we will consider only a quarter model of the RV (Fig. 1) [1,11]. Hence, the RV system has only eight degrees of freedom represented by the generalized coordinate vector **q**:

$$\boldsymbol{q} = [\bar{y}, \bar{\alpha}, y_1, \alpha_1, y_{11}, \alpha_{11}, y_{12}, \alpha_{12}]^{\mathrm{T}} \tag{1}$$

In this study, the rail is assumed to be smooth and rigid. Moreover, due to the fact that the rail curve radius and the RV speed are constant, damping forces were found not to be important, compared to the elastic ones [1,11].

We may find the dynamic model of the RV system by applying the Lagrange method:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_i \tag{2}$$

L is the Lagrangian function and Q_i represents the generalized forces applied to the system.

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