GLOBAL SENSITIVITY ANALYSIS AND MULTIOBJECTIVE OPTIMIZATION OF BOGIE SUSPENSION

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Summary Multiobjective optimization of nonlinear multibody systems with many degrees of freedom is a burdensome computational challenge. A feasible practical methodology for global sensitivity analysis (GSA) of multibody systems with respect to design parameters is proposed based on the multiplicative dimensional reduction method. The computational efficiency of optimization is significantly improved by restricting the input design parameters only to those identified by the GSA. The methodology is applied for GSA of a railway vehicle dynamics with respect to the bogie suspension characteristics. Several multiobjective optimization problems are then formulated and solved for a railway vehicle model with 50 degrees of freedom using genetic algorithm. The results obtained yield practical information regarding the optimized bogie suspension properties which improve the dynamics behavior of the vehicle from various perspectives. The proposed algorithm can be used in design optimization of nonlinear multibody systems with different applications.

INTRODUCTION

Bogie primary and secondary suspension stiffness and damping components can affect railway vehicle dynamics behavior from different perspectives such as safety, ride comfort, and wheel/rail contact wear. The bogie suspension components might have conflicting effects on the system dynamics. Furthermore, vehicle's speed, track irregularities, and radius of curvature of the track can also affect the vehicle's dynamics. Therefore, to satisfy various design requirements it is necessary to formulate and solve multiobjective optimization problems for railway vehicles modeled as multibody systems.

Multiobjective optimization problem of a nonlinear multibody system with many degrees of freedom (DOFs) is an elaborate task which requires high computational efforts. Number of input design parameters is one of the most critical issues which can significantly affect the computational burden of the optimization. Sensitivity analysis makes it possible to recognize those design parameters that most affect the system dynamics response and attenuate the number of inputs for optimization. Here, an efficient method for the GSA of multibody systems is proposed. The methodology is then applied for the GSA and optimization of a railway vehicle dynamics with respect to suspension stiffness and damping components.

GLOBAL SENSITIVITY ANALISYS

The Monte Carlo simulation is one of the most common methods for GSA. But the main drawback is heavy computational effort which makes it unfeasible to be applied to complex multibody systems. Analysis of variance decomposition or high dimensional model representation (HDMR) decomposes the response function of a high dimensional system into a combination of a set of low dimensional systems and dramatically reduces the computational and sampling efforts. Zhang and Pandey [1] proposed a multiplicative form of the dimensional reduction method (M-DRM) for GSA. The main advantages of using such an approximation are simplicity, high accuracy, computational efficiency, and closed-form representation for the global sensitivity indices. Based on the HDMR and M-DRM concepts the closed-form formulation of the global sensitivity index of an objective function with respect to the ith design parameter x_i is introduced as:

$$S_i^{\mathrm{T}} \approx \frac{1-\alpha_i^2/\beta_i}{1-\left(\prod_{k=1}^{n}\alpha_k^2/\beta_k\right)} \tag{1}$$

where S_i^{T} is the total sensitivity index. Variables α_k and β_k are calculated using the Gaussian quadrature integration method, see, e.g. [2]. It has been shown that these indices are as accurate as those obtained from the Monte Carlo simulation but with a dramatically less computational effort. Here, this methodology is employed to evaluate the sensitivity of different objective functions such as ride comfort ($S_{\Gamma_{\mathrm{C}}}^{\mathrm{T}}$), wear ($S_{\Gamma_{\mathrm{W}}}^{\mathrm{T}}$), and three safety criteria namely track shift force ($S_{\Gamma_{\mathrm{TS}}}^{\mathrm{T}}$), risk of derailment ($S_{\Gamma_{\mathrm{RD}}}^{\mathrm{T}}$), and running stability ($S_{\Gamma_{\mathrm{St}}}^{\mathrm{T}}$) of a one-car railway vehicle with respect to the 14 bogie suspension components listed in Table 1.

Table 1: Design parameters for sensitivity analysis.

No	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Parameter	k_x^{p}	c_x^{p}	k_y^{p}	c_y^{p}	k_z^{p}	c_z^{p}	k_x^{s}	c_x^{s}	k_y^{s}	c_y^{s}	k_z^{s}	c_z^{s}	k^{AR}	k^{TR}

Here, k and c denote stiffness and damping values, respectively. The subscripts x, y, z indicate the longitudinal, lateral, and vertical directions, respectively. The superscripts p, s, AR, and TR denote primary, secondary, anti-roll bar, and traction rod

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components, respectively. The simulations are carried out and analyzed for a vehicle running at maximum admissible speed on a curved track with very small radius of curvature *R*=300 m.

MULTIOBJECTIVE OPTIMIZATION

The GSA results shown in Fig. 1(a) are obtained with merely 168 simulations and include informative data regarding the design optimization of bogie suspension components. As an example, to reduce contact wear and improve ride comfort only parameters number 1, 3, 7, 8, and 11 can be considered as the design parameters in the multiobjective optimization problem. Therefore, the fourteen initial variables are reduced to five. This significantly improves the computational efficiency of the optimization. The wear/comfort Pareto optimization can be formulated as follows: for a given vehicle model, prescribed structural parameters, feasible initial states, and a set of operational scenarios it is required to determine the optimized vector of the design parameters ($\mathbf{d}^*$) such that the variational equation $\boldsymbol{\Gamma}(\mathbf{d}^*) = \min_{\mathbf{d}\in\Omega} \boldsymbol{\Gamma}(\mathbf{d})$ is satisfied subject to the following constraints: $\Gamma_{TS}(\mathbf{d}^*) \le \Gamma_{TS}^{max}$, $\Gamma_{St}(\mathbf{d}^*) \le \Gamma_{St}^{max}$, $\Gamma_{RD}(\mathbf{d}^*) \le \Gamma_{RD}^{max}$. Here, $\boldsymbol{\Gamma} = [\Gamma_W \quad \Gamma_C]^T$ is the vector of objective functions and Ω is the domain of the input design variables (**d**). Limits Γ_{TS}^{max}, Γ_{St}^{max} and Γ_{RD}^{max} are the maximum admissible values of the track shift force, stability and risk of derailment considered as thresholds to the optimization problem.

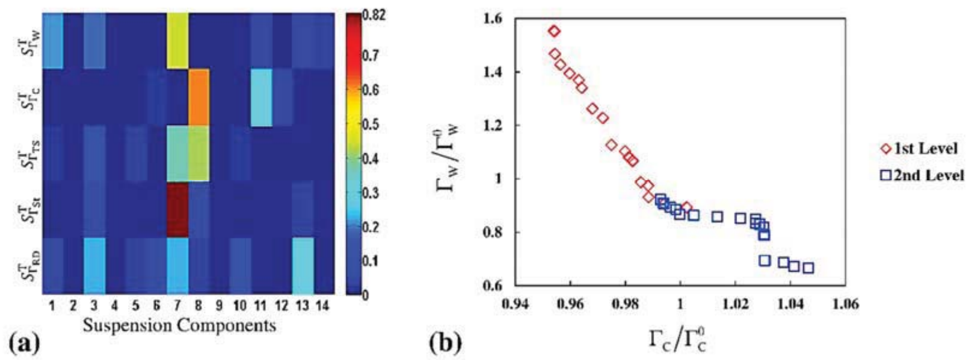

Figure 1: a) GSA results of a one-car railway vehicle with 50 DOFs with respect to the suspension components; b) Normalized wear/comfort Pareto front.

To further improve the computational efficiency the five design parameters recognized by the GSA are classified into two sets (first set with 3 and second set with 2 design parameters) and the wear/comfort Pareto optimization is accordingly carried out in two levels. The formulated problem is solved using a genetic algorithm (GA) based routine integrated in a MATLAB/SIMPACK co-simulation interface. The normalized wear/comfort Pareto front achieved by the first and second optimization levels are compared in Fig. 1(b). The results proved that it is possible to reduce contact wear and improve ride comfort for the considered railway vehicle model while a satisfactory safety level is guaranteed.

CONCLUSIONS

This study showed the feasibility and efficiency of the proposed M-DRM based method for the GSA of multidimensional nonlinear multibody systems which provided the results in a computationally efficient framework. The proposed methodology has been used for the GSA of a one-car railway vehicle dynamics behavior with respect to the bogie suspension components and revealed remarkable practical results which significantly reduced the number of input design parameters for optimization. The analysis of the GSA and Pareto optimization results showed that it is possible to solve optimization problem of a railway vehicle with realistic structural parameters and track irregularities in a computationally efficient manner and reduce wear and improve comfort while a satisfactory safety level is guaranteed. The proposed methodology can be used in the GSA and design optimization with different applications.

ACKNOWLEDGMENTS

The Ekman family foundation which is cordially appreciated for the financial support of this research.

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