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Multibody approach in suspension system optimization

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In this paper an approach of optimization of suspension system parameters is described. Taking into consideration the stiffness and damping coefficients of springs and shock absorbers of a heavy road transport vehicle semitrailer, process of adjusting those values has been undertaken by means of the response surface methodology and a desirability function application, supported by the sensitivity computations. Two different methods of constructing metamodels: Kriging and polynomial regression have been tested and compared with a set of results obtained from the numerical multibody dynamic analysis. The objective of the undertaken efforts was to minimize the loads in the crucial points of the structure, identified as the high-risk failure areas. A number of simulations have been carried out under the set of different load cases, specially established to represent a wide range of operating conditions possible to be met during the vehicle life cycle.

Keywords: multibody modeling, lightweight structures, response surface method, dynamics of multibody system.

1. Introduction

A multibody dynamic analysis [1] is a fast and reliable way of calculating kinematic and dynamic quantities in compound mechanisms. It helps to estimate values of internal reactive forces acting between the elements of the analyzed assembly. Those, in subsequent design process can be used as inputs during the finite element method (FEM) analysis, making it more reliable and accurate due to the application of more realistic loading conditions. Moreover, those preliminary dynamic simulations can be augmented by the exploitation of flexible body parts, what leads to significant improvements in accuracy of the method.

Response surface methodology (RSM) described in [12, 13, 18–20, 26] is applied to provide the theoretical values of the output variable, based on the data gathered during the experimental measurements that are usually carried out in specially predefined order. Controlled iterative modifications of the design variables provided by the design of experiment (DOE), allows exploration of the design space and yields the information needed for later data approximation. For the last three decades a significant development of this group of methods has been observed, what resulted in a vast spectrum of new algorithms with simultaneous improvements of already existing techniques. They are commonly expanded into multi-objectives problems; nevertheless, in the presented work a desirability function has been implemented to compound multiple outputs into one, comprehensive surrogate. Detailed explanation and description of the possible modifications can be found in the provided literature: [5, 9] and [16].

In order to understand the design variable influence on the output quantity and gather acquaintance about the level of their dependency, the sensitivity analysis is carried out [11]. Reliability and robustness of this method, described in [15] and [21], and the possibility of its application in different fields of engineering makes it a universal way of understanding the behavior of the tested structure.

The problem of adjusting the operational parameters of a suspension system in heavy-duty road vehicles has been investigated by many researchers. The early methods consisted of trial-and-error attempts and simplified analytical models. One of the first numerical models used for suspension tuning appeared in 1967. It was developed by E.K. Bender et al. and it is described in [3]. Comprehensive description of the techniques used for finding the optimal solution by means of computer aided analysis is given by El-Madany in [10]. He focused on damping factor for six degree-of-freedom linear tractor semitrailer model. A very interesting attempt is presented by D.W. Blue and B.T. Kulakowski in [4], in which distinct performance measures are taken into consideration: handling stability, breaking efficiency, ride comfort and pavement damage with simultaneous consideration of sensitivity analysis. D.J. Cole and D. Cebon in [6] describe an effort of decreasing the dynamic tire forces in tandem suspensions of an articulated trailer. In this work, a test rig used for measuring the quasi-static performance and a numerical simulation complemented by the validation on a test vehicle are presented. Same authors in [7] establish a guideline for designers of the passive suspension systems for large lorries, providing an optimization procedure robust to payload and speed changes. Methods described in the above mentioned literature positions give a wide scope of the possible optimization techniques of the dynamics of heavy-duty semitrailers.

2. Problem formulation

The main objective of the work described in this paper was to adjust the suspension parameters of the articulated trailer in order to minimize the forces in crucial areas of the construction. The up-to-date techniques have been employed, taking the advantage of multibody dynamics simulations, sensitivity analysis and multi-objective optimization based on the response surface methodology compound with a desirability function. The obtained dynamic results have been provided as inputs for further advanced strength computations using the finite element method.

The above-mentioned high-risk areas were specified as: the kingpin (front bolt) connecting the truck and the articulated trailer; the bolt of the dump body at the rear end and the actuator mounting point, in which the lifting mechanism operating the dump body is connected to the semitrailer chassis. They were defined as the most loaded and critical regions of the examined structure, based on the preliminary FEM analysis. Because a semitrailer can be used under different operational conditions, several, corresponding to the reality, types of simulations have been carried out. After obtaining the data from a number of them, the parametric and structural sensitivity analyses have been performed, in order to define the worst operating conditions. Based on the results mentioned above, metamodels have been elaborated using Kriging and polynomial regression techniques. The aim of this activity was to compare results supplied by both of them, with values pointed out by the numerical simulations. The following desirability function computations have led to the optimal values of the stiffness k and damping ratio α coefficients, which are responsible for maintaining the optimal conditions of transferring excitations from wheel hubs to the body of the structure.

3. Model and simulation conditions

A multibody model composed of rigid and flexible components has been prepared. In the most general description two main parts can be derived: tractor and semitrailer. The first one has been modeled in very simplified manner, due to its role in simulations, which mainly consist of forcing the movement with specified kinetic parameters: trajectory, velocity, acceleration and a specified rate of the acceleration change. Although the forces in this mechanism lie out of the field of interest, its behavior has a noticeable influence on the measurements that are taken into consideration. Therefore, an effort has been undertaken to supply a set of proper suspension parameters assuring a realistic dynamic response. The second component of the virtual mechanism is the key part of the simulated vehicle. Flexible frame and dump body have been prepared in commercial MSC Nastran/Patran environment, dealing with the finite element analysis and pre- and post-processing of the analyzed models. Two separate output files contain information about the geometry and the modal analysis results: eigenvalues (i.e., natural frequencies) and eigenvectors which are used for computing the response of the system, which depends on the excitation forces. The principle of modal superposition is applied to combine the mode shapes at each time step of the simulation to reproduce the total deformation of the flexible bodies. For maintaining the most accurate results, the modal analysis has been carried out for the model under every considered load case separately. During the computational process that is run under the set of load cases corresponding with the real operational conditions, flexible elements are under excitation what results in their dynamic behavior. This approach is more realistic, by the reason of considering inevitable strains that influence the measured quantities.

The weight of maximum amount of cargo that can be carried by the construction is at the level of 32 t, and that was the mass that acted on the virtual semitrailer. To fulfill the requirements of the realistic modeling procedure, different load cases had to be specified, to make the simulations as close to the real working conditions as possible. Therefore, except cargo uniformly distributed on the dump body floor, the situation of concentrating it in one, smaller area has been examined. Hence, the assumption had been undertaken that the bottom of the box would be divided into six smaller areas, where 25% of the maximum carriage capacity would be applied separately. The remaining five areas would work under 4.708 kN (15%). The construction symmetry allowed to decrease the amount of numerical experiments, with the load mass concentrated only on one side, along the longitudinal axis. It was sufficient for satisfying all of the requirements. This situation is illustrated in Fig. 1.

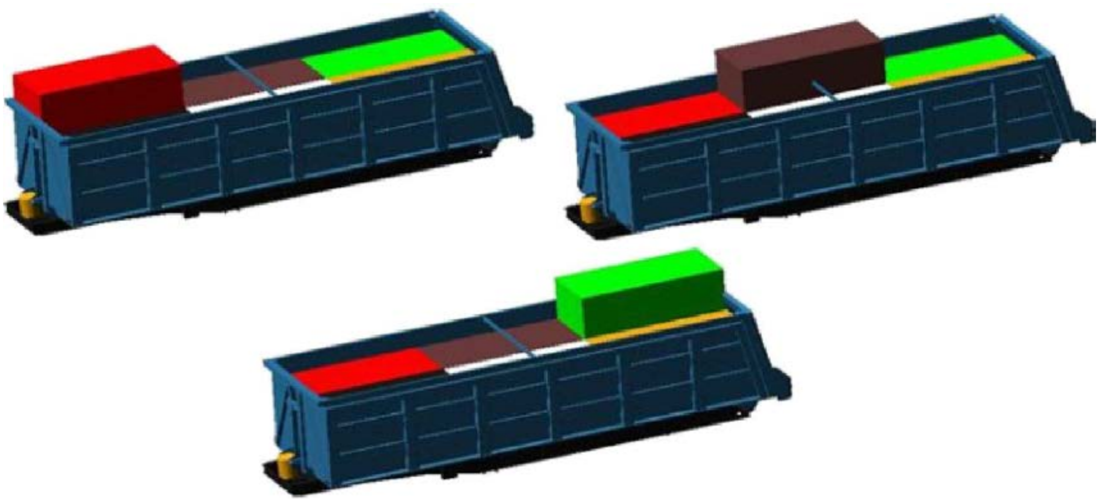


Fig. 1. Non-uniform cargo distribution. Simulations made only for one-sided changes, because of the construction symmetry.

The simulations have been performed under two different road conditions. The first was an uneven country road where the vehicle travelled with lower velocity, the second – a flat track with local asphalt pavement losses, nevertheless allowing the lorry to travel faster. Only the second case has been used for further analysis, since it generates greater values of the forces being investigated, which is depicted in Fig. 2.

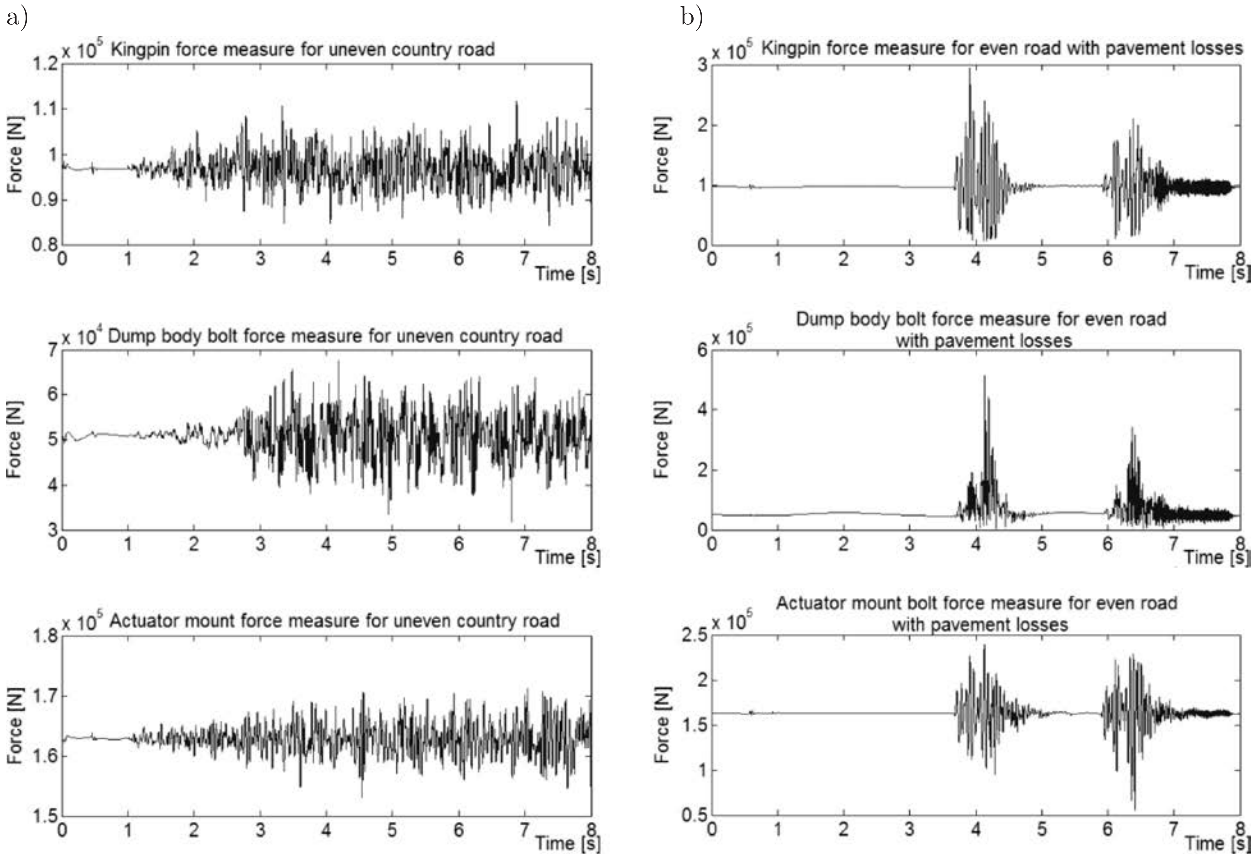


Fig. 2. The comparison of the acquired force values from the simulations on uneven country roads (a) and even roads with asphalt pavement loss (b).

4. Sensitivity analysis

The main idea of performing the sensitivity analysis was to examine the influence of different load cases and velocities together with specific road conditions on the measured forces. As mentioned above, the road pavement type that supports more significant values of the responses has been considered for all of the simulations.

The sensitivity analysis provided the answer to the question: which parameter had the greatest effect on the responses in the semitrailer's crucial points. The vehicle's speed, stiffness k and damping coefficient α were changed in a number of attempts, providing complete information about their level of influence. An example of force-time characteristic for the dump body bolt from one of the trials is shown in Fig. 3.

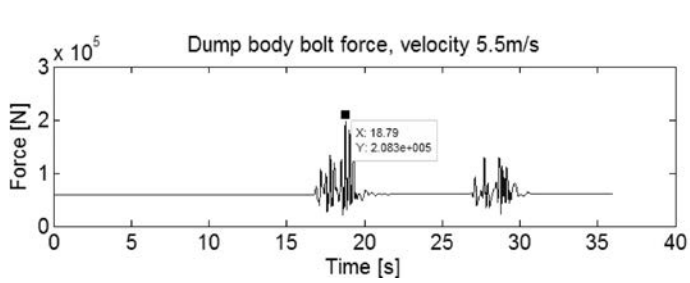


Fig. 3. The dump body bolt force value for the basic parameters. The maximum peak value for the measured force: $2.083 \cdot 10^5$ N.

The test was carried out on a flat road with double local pavement loss, with the truck velocity of 5.5 m/s, the uniform load case of 32 t and with suspension parameters corresponding to the baseline solution. Figure 4 shows the graphical representation of the same force measurements in time domain for corresponding operational conditions, but with increased stiffness coefficient k for the springs in the suspensions. The results show that the maximum value of the force during surmounting the obstacles changed from $2.083 \cdot 10^5$ N to the value of $2.146 \cdot 10^5$ N.

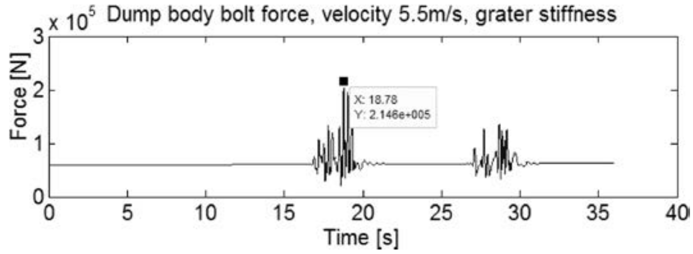


Fig. 4. Dump body bolt force value for increased k stiffness coefficient. The maximum peak value for the measured force: $2.146 \cdot 10^5$ N.

To perform a sensitivity analysis, the finite difference principle was used, with a forward approximation approach. Equation (1) provides an absolute value, which cannot be compared with sensitivities calculated for different types of the assumed parameters.

$$\frac{\Delta R_i}{\Delta P_j} = \frac{R_i\left(P_j + \Delta P_j\right) - R_i\left(P_j\right)}{\Delta P_j}, \tag{1}$$

where R_i is a response quantity, and P_j is the analyzed model property. If they are to be commensurable, the following equation expressing normalization has to be used:

$$S_n = \frac{\Delta R_i}{\Delta P_j} \cdot \frac{P_j}{R_i}, \tag{2}$$

where S_n is a relative sensitivity normalized with respect to the response value. It is dimensionless; hence, suitable for comparison with results obtained for other parameters P_j. The outcomes of this type of the analysis are usually presented on a Pareto graph that facilitates the understanding of the factors participation level. The example related to the model with uniform distribution of a cargo is shown in Fig. 5.

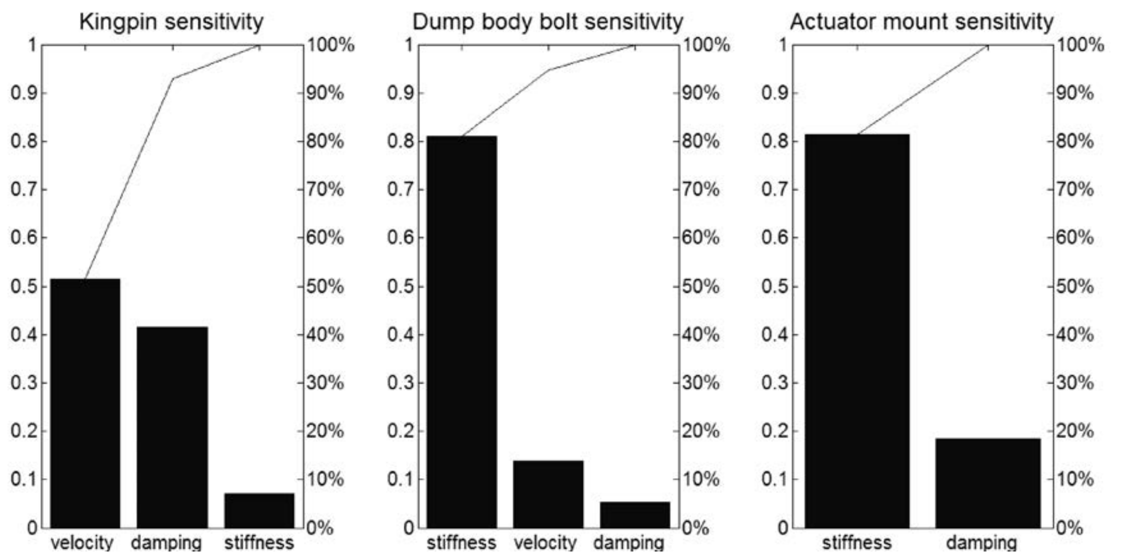


Fig. 5. Pareto graph showing the measured forces sensitivity level, related to changed parameters: velocity, damping and stiffness coefficients.

The lack of presence of the third result of the sensitivity analysis for the actuator mount, is due to the negligibly small influence of the velocity variations. Taking into consideration the above, together with an assumption that greater speed of the vehicle will result in higher force values, the decision has been made, to perform further simulations on a flat road model with local obstacles and with the highest velocity allowed for the lorries: 90 km/h.

5. Metamodeling

To build the response surfaces, five-level full factorial design of experiment has been applied, what for two design variables (i.e., stiffness k and damping α coefficients) has provided 25 simulations. Computations have been performed for all of the models, with different cargo distribution. In each case k and α coefficients have been changed, by means of additional values: ik and $i\alpha$, which were used as follows: a *new stiffness* $=$ *ik* $\cdot$ *the basic stiffness*, and a *new damping* $=$ *iα* $\cdot$ *the basic damping*. The spectrum of changes of the factors ranged from 0.5 to 1.5 with 0.25 step for each parameter, with assumption that initial conditions were with both coefficients equal to 1.0 ($ik = i\alpha = 1.0$). It represents the characteristics of springs and shock absorbers usually used in this type of vehicles.

The response surfaces have been created for every measured force and for every model separately, using two different methods: Kriging and polynomial regression. DACE Toolbox for Mathworks Matlab has been exploited to create the response surfaces constructed by means of the first method. A polynomial regression has been computed using the standard Matlab functions.

A Kriging model assumes that predicted values are a combination of a known function $f_j(x)$ and departures from the form:

$$\widehat{y} = \sum_{j=1}^{k} \beta_j f_j(x) + Z(x), \tag{3}$$

where $Z(x)$ is a realization of a stochastic process with mean zero and a spatial correlation function given by:

$$\operatorname{cov}\left[Z\left(x_i\right), Z\left(x_j\right)\right] = \sigma^2 R\left(x_i, x_j\right), \tag{4}$$

where σ^2 is a process variance and R is a correlation. Many correlation functions can be chosen, however a Gaussian one is the most frequently adapted and has also been used in this project.

The most common polynomial models of approximating a response function are the first- and second-order regressions. In general, they can be expressed as:

$$\widehat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i \tag{5}$$

for the first order, and:

$$\widehat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=1, i<j}^{k} \beta_{ij} x_i x_j \tag{6}$$

for the second one.

According to Myers and Montgomery [20] in some situations, approximating polynomials of order greater than second can be used. Because of the strong nonlinearities of the outputs, a polynomial regression model of the fourth order has been adopted to fit the results obtained from the simulations.

The exemplary results for the model with uniformly distributed cargo, acquired from both methods are presented in Fig. 6. The black dots represent the output values from the simulations for specified k and α factors.

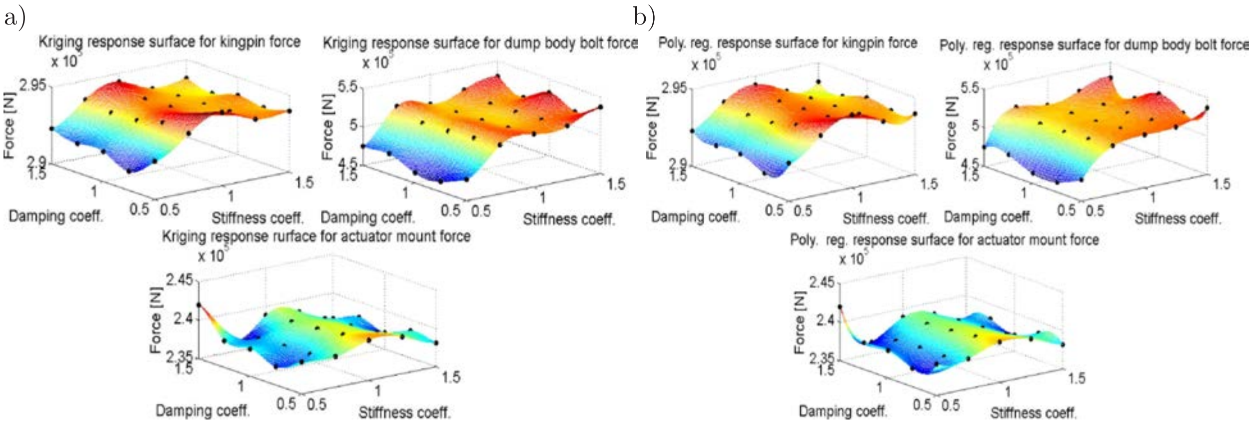


Fig. 6. Response surface acquired from the Kriging method (a) and the polynomial regression (b).

Each metamodel has been constructed on the basis of the maximum force value of a particular simulation.

6. Desirability function

The process of finding the optimal solution for all of the measured forces is a typical multi-objective problem; three objectives were assumed to be minimized simultaneously. Furthermore, due to the changes in the type of load cases, a number of outputs supposed to be minimized have been increased to 12 (three forces and four load cases). Finding the most appropriate solution for the stated optimization problem, considering all of the surrogates could become computationally complicated and time consuming. Therefore, the decision to reduce the multi-objectivity to a simpler and faster exploration of single-function extremes has been made. The transformation that preceded the search for the optimum has been carried out by means of desirability function.

In cases similar to the described problem, the most intuitive approach is to superimpose all the response plots and determine the optimal solution by finding a global minimum (maximum). However this method has poor robustness and often indicates wrong solutions. The alternative approach, suggested in [14] and later modified in [8] assumes that a scale-free value $d_j \in (0;1)$ is assigned to a response j, and increases when the value of j-th response is getting more appropriate (desired). It can be expressed as:

$$d_j\left(y_j(x)\right) = \begin{cases} 1 & \text{if} \quad y_j(x) \le y_j^{\min}, \\ \left(\dfrac{y_j^{\max} - y_j}{y_j^{\max} - y_j^{\min}}\right) & \text{if} \quad y_j^{\min} \le y_j(x) \le y_j^{\max}, \\ 0 & \text{if} \quad y_j(x) \ge y_j^{\max}, \end{cases} \tag{7}$$

where $y_j^{\min}$ and $y_j^{\max}$ are the lower and upper boundaries of the desired values of the response function $y_j(x)$. The overall desirability D is a weighted geometric mean, combining the d_j values:

$$D = \left(d_1^{w_1} d_2^{w_2} \ldots d_n^{w_n}\right)^{\frac{1}{\sum w_j}}, \tag{8}$$

where w_n are the responses weights.

In the case of desirability functions for the semitrailer, because of the need of minimization of the forces at the crucial points of the construction, the target value was set to the global minimum $y_j^{\min}$ of a particular response surface (forces values), therefore a global maximum $y_j^{\max}$ was the worst case, hence $d_j\left(y_j^{\max}(x)\right) = 0$. For each load case model the overall desirability function D_l have been expressed as:

$$D_l = \left(d_{fb} \cdot d_{dbb}^2 \cdot d_{amp}\right)^{1/4}, \qquad l = 1, 2, 3, 4, \tag{9}$$

where l is a particular load case and d_{fb}, d_{dbb}, d_{amp} are the desirability values for the front bolt, dump body bolt and actuator mount point responses respectively. Because of the non-uniform cargo load case, the values of first and third forces decrease, when dump body bolt force increases, hence it is impossible to minimize all of them at the same time: the trade-off value needs to be found. To prevent an extreme build-up of the mentioned quantity, d_{dbb} weight has been set to 2. The overall desirability for all the simulated models of the articulated trailer was expressed as:

$$D = \left(D_1^2 \cdot D_2 \cdot D_3 \cdot D_4\right)^{1/5}. \tag{10}$$

Because evenly distributed cargo is the most common load case in the reality, it has weight of 2 in the optimization process. The same method has been used for Kriging and polynomial surrogates. The example of response surfaces for a non-uniformly loaded cargo and desirability surface is shown in Fig. 7. Using the formulation explained above, the most appropriate trade-off values of stiffness and damping coefficients have been computed for this particular case. In Fig. 7, large bullet points indicate force values resulting from the chosen k and α.

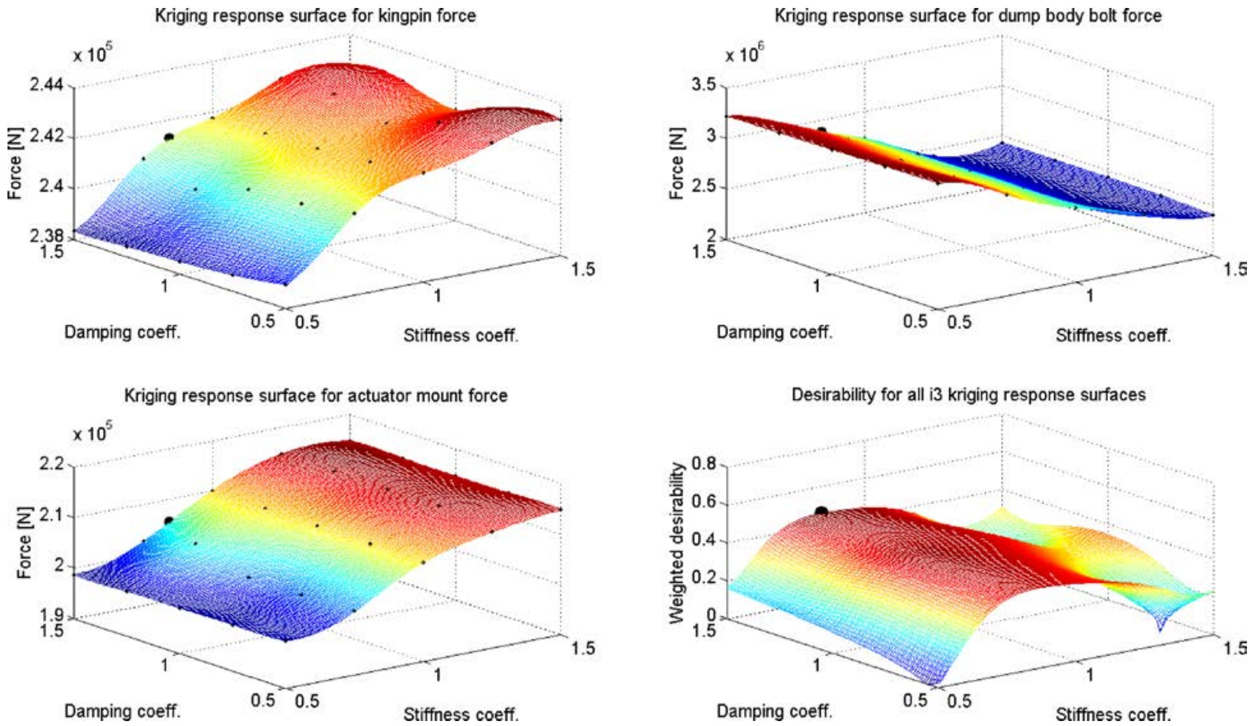


Fig. 7. The response surfaces for non-uniform cargo load with desirability surface for this particular case (Kriging metamodel).

The final k and α coefficients for the analyzed semitrailer have been computed on the basis of the overall desirability function for all of the models (i.e. all the load cases). Both resultant Kriging and polynomial surfaces are depicted in Fig. 8. The marked dots are the global optimal solutions, indicating the stiffness and damping coefficients being the chosen trade-offs for each metamodeling technique Areas where overall desirability function equals to zero correspond to the

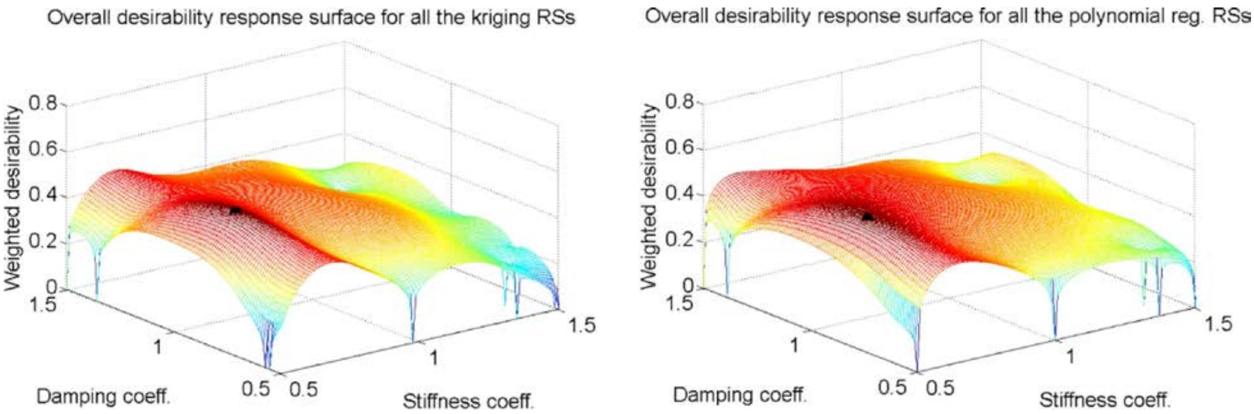


Fig. 8. The global desirability function obtained from Kriging and polynomial surrogates. The marked points are the global optimums.

local maximums for the partial surrogates, hence are treated as the worst solutions in undertaken optimization search (i.e., $D = 0$).

The obtained solution, as it is often in the case of the multi-objective optimization, strongly depends on the formulation of the desirability function itself (i.e., the assumed weights). Therefore, additional effort has been made to calculate the sensitivity of the optimal solution with respect to the parameters of the desirability function. Using the formulations introduced in the previous paragraph, the evaluation has led to the results depicted in Fig. 9. Charts in the picture indicate the level of changes of the stiffness and damping coefficients, regarding to the alteration of the weights in the overall desirability function. All the parameters were changed separately and the rate of change has been set to 1. Both of the obtained metamodels have been examined.

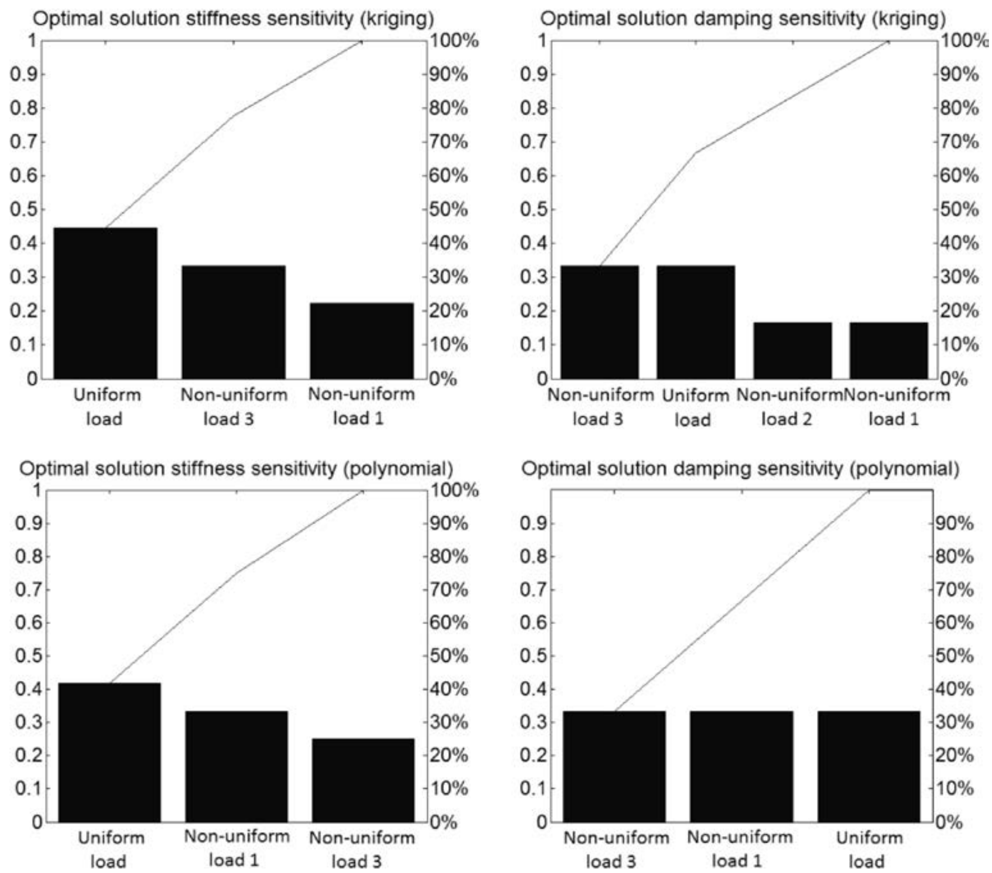


Fig. 9. Sensitivity of the optimal solution regarding to the changes in the desirability function weights.

7. Results check and metamodeling techniques comparison

For each load case a local optimization has been carried out, which has resulted in finding the best parameters for the examined scenario. In Fig. 10, the surrogates for the non-uniform cargo are presented, with the overall desirability surface modeled for this particular case and the bullet points indicating force values for the computed optimal coefficients. The search for the most optimal result has been carried out by means of the desirability surface exploration and finding the maximum value.

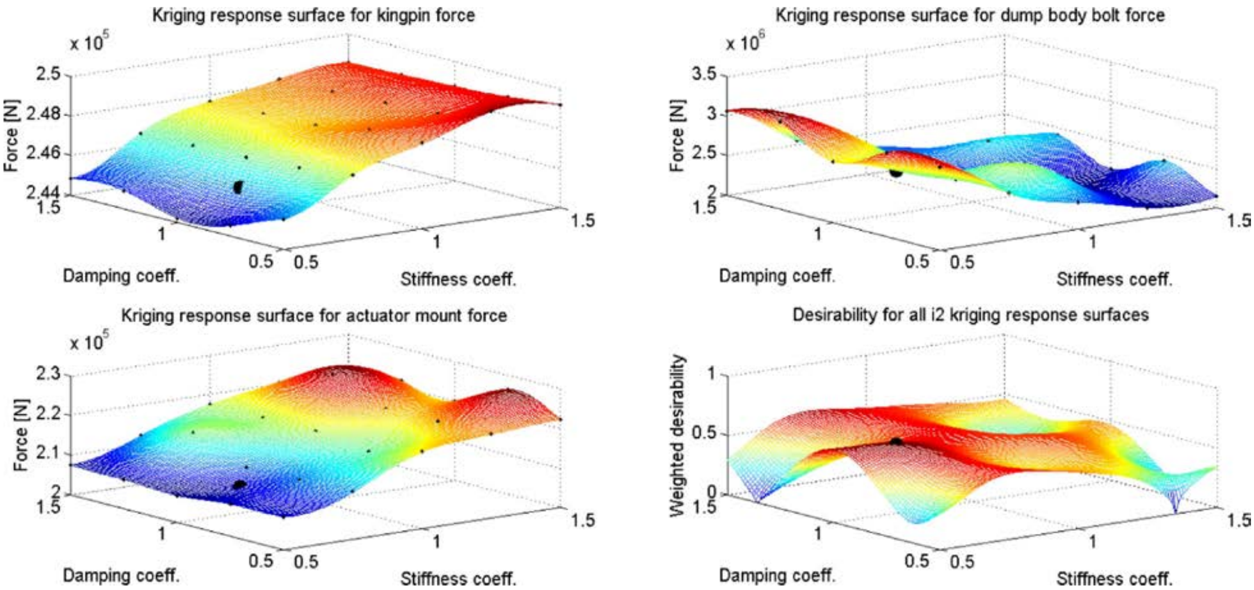


Fig. 10. Kriging surrogates and desirability surface for the non-uniform cargo load case, with indicated force values for the optimal stiffness and damping coefficients, found in local optimization process.

To study the correctness and accuracy of the metamodels built, the force values indicated as the local optimal solutions on both metamodels have been compared with the results obtained from the simulations. The comparative studies are shown below, in Table 1; while the relative differences obtained from the simulations are depicted in Fig. 11.

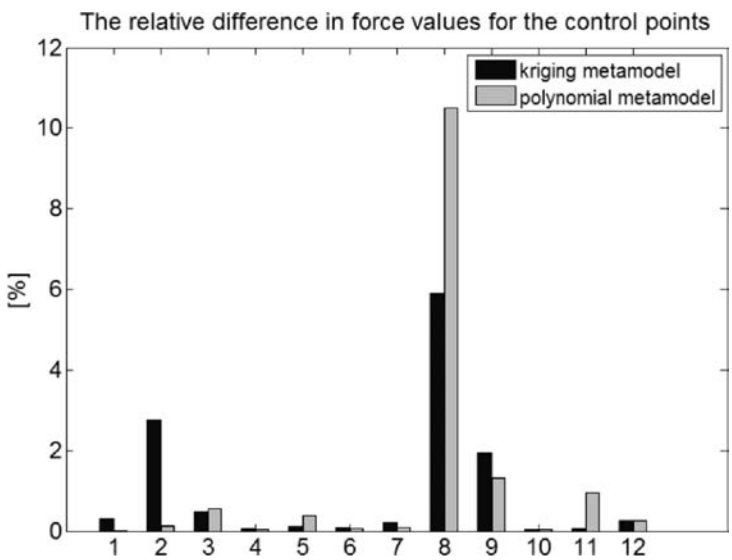


Fig. 11. The relative differences between predicted and computed force values. Quantities 1 – 12 (horizontal axis) explained in Table 1.

Table 1. The comparison of the predicted and computed force values (for both metamodeling techniques), for the local optimal stiffness and damping solutions.

		Local optimal ik and $i\alpha$ values from Kriging metamodel	Predicted force value from Kriging metamodel [N]	Simulation force value for ik and $i\alpha$ from Kriging metamodel [N]	Local optimal ik and $i\alpha$ values from polynomial metamodel	Predicted force value from polynomial metamodel [N]	Simulation force value for ik and $i\alpha$ from polynomial metamodel [N]
Uniform load	Front bolt (1)	$ik = 0.5000$ $i\alpha = 0.7828$	292132.7	291251.5	$ik = 0.5000$ $i\alpha = 0.7323$	291258.5	291213.3
	Dump body bolt (2)		475427.8	462355.1		463782.0	464385.8
	Actuator mount (3)		238622.6	237451.9		238659.0	237322.5
Non-uniform load, case 1	Front bolt (4)	$ik = 0.8030$ $i\alpha = 1.5000$	262239.2	262385.3	$ik = 0.8030$ $i\alpha = 1.5000$	262239.2	262342.6
	Dump body bolt (5)		2605041.0	2608243.9		2605041.0	2614866.0
	Actuator mount (6)		228211.7	228020.3		228211.7	228042.4
Non-uniform load, case 2	Front bolt (7)	$ik = 0.6616$ $i\alpha = 0.9141$	246200.9	245682.3	$ik = 0.6111$ $i\alpha = 0.8636$	245784.7	245595.1
	Dump body bolt (8)		2795918.0	2630994.2		2893697.0	2589721.6
	Actuator mount (9)		212419.4	208284.2		210474.7	207688.9
Non-uniform load, case 3	Front bolt (10)	$ik = 0.8434$ $i\alpha = 1.5000$	241161.9	241272.3	$ik = 0.8939$ $i\alpha = 1.5000$	241393.2	241315.4
	Dump body bolt (11)		2879998.0	2881842.7		2825931.0	2853151.2
	Actuator mount (12)		206029.0	205472.5		207532.6	207005.8

As proposed in [5], the root mean square error (RMSE) measure can be applied for validation of the surrogates. This measure gives an overall assessment of the metamodel, and is expressed by the formula (11):

$$\mathrm{RMSE} = \sqrt{\frac{\sum\limits_{i=1}^{m} (y_i - y_i')^2}{m}}, \tag{11}$$

where m is a number of validation points, y_i' is a predicted value of the observed value y_i from the numerical simulation. The lower the value of RMSE, the more accurate the metamodel is. In order to provide more intuitive assessment, the overall average accuracy (OAA) has also been estimated, as an average value of the relative differences, by means of the dependency (12):

$$\mathrm{OAA} = \frac{\sum\limits_{i=1}^{m} \left| \dfrac{y_i - y_i'}{y_i} \right|}{m} \quad [\%]. \tag{12}$$

The results of the accuracy estimation are presented in Table 2.

Table 2. Accuracy assessment for the obtained metamodels.

	RMSE [N]	OAA [%]
Kriging metamodel	47788.00	1.0609
Polynomial metamodel	88151.76	1.2996

A desirability method has been implemented, with special care taken for defining the weights for the geometrical mean elements (Eq. (8), (9) and (10)), which define the component importance level. Using this technique, the optimal solution of stiffness and damping coefficients for the analyzed suspension system have been found. The global results obtained from Kriging and polynomial metamodels are presented in Table 3.

Table 3. The optimal solutions obtained by using both RS techniques.

	Stiffness coefficient ik	Damping coefficient $i\alpha$
Kriging metamodel	0.6414	0.8939
Polynomial metamodel	0.6010	0.8636

In Fig. 12 all the polynomial response surfaces are shown, with the bullet points indicating force values for the global optimization solutions.

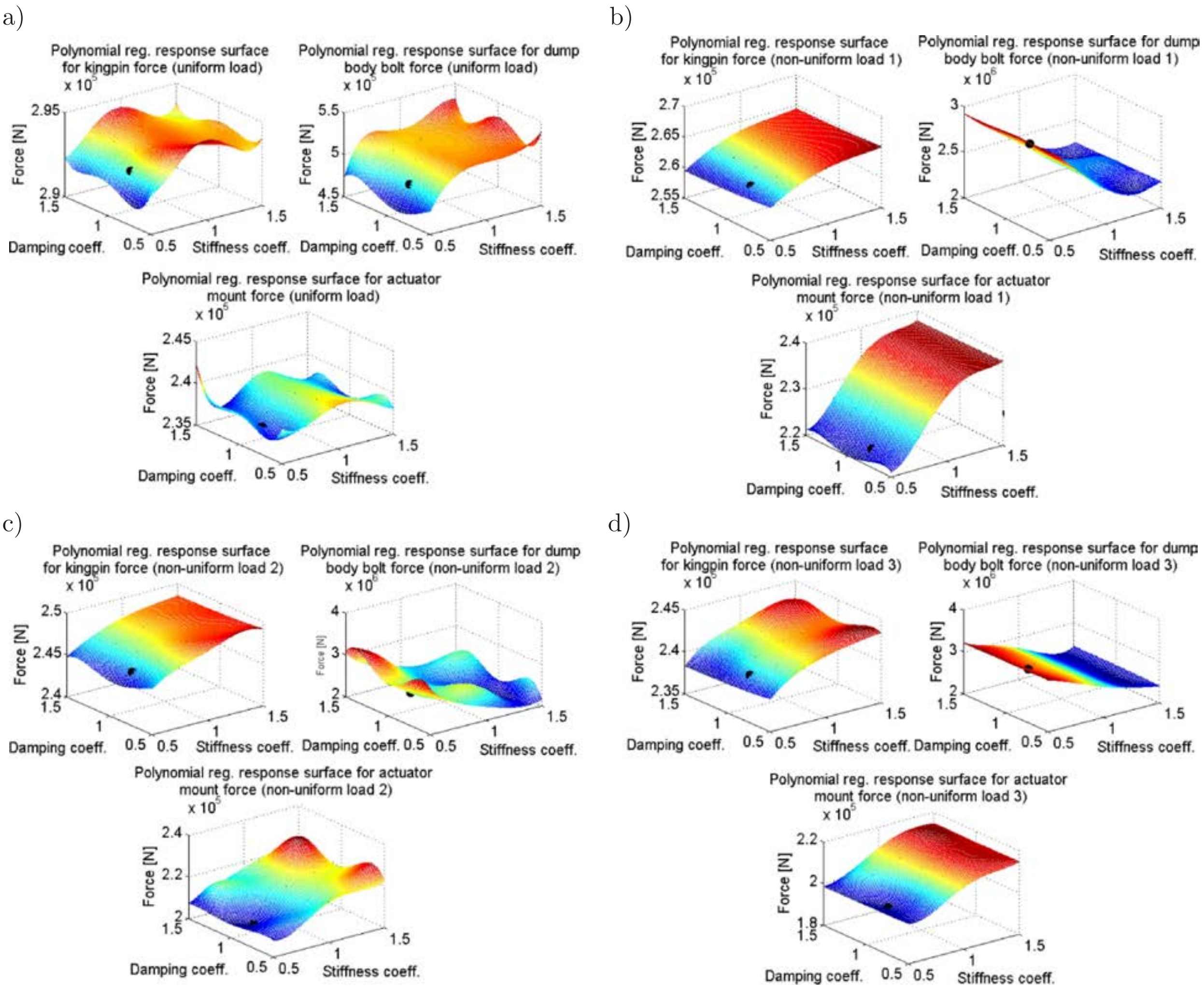
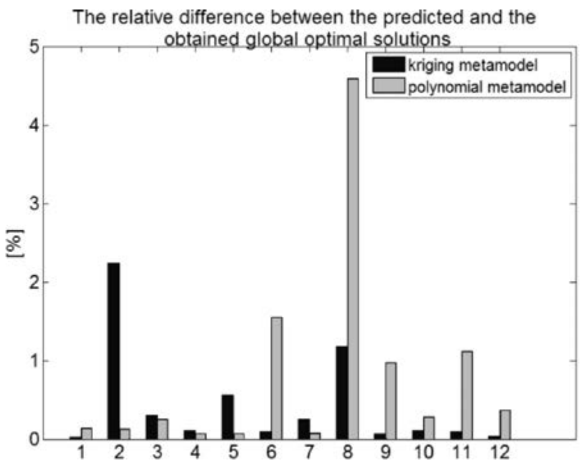


Fig. 12. The polynomial response surfaces for each loading case model: a) uniform cargo distribution and b), c), d) non-uniform distributions, as depicted in Fig. 1.

For the final results presented in Table 3, simulations for each load case have been carried out separately. The obtained force magnitudes have been compared to the values predicted by both types of surrogates and also to the forces resulting from the application of initial damping and stiffness ($ik = 1$, $i\alpha = 1$). The comparison is shown in Table 4 and in Fig. 13.

Table 4. The comparison of predicted and obtained from numerical experiments force values (for both metamodeling techniques), for the global optimal stiffness and damping coefficients.

		Simulation force value for optimal ik and $i\alpha$ from Kriging metamodel [N]	Predicted force value from Kriging metamodel for optimal ik and $i\alpha$ [N]	Simulation force value for optimal ik and $i\alpha$ from polynomial metamodel [N]	Predicted force value from polynomial metamodel for optimal ik and $i\alpha$ [N]	Simulation force for initial values of stiffness and damping [N]
Uniform load	Front bolt (1)	292798.8	292714.7	292404.4	292822.0	293931.4
	Dump body bolt (2)	497655.4	486478.0	490953.7	490322.1	513380.0
	Actuator mount (3)	237054.2	237768.0	236832.7	237421.3	239400.0
Non-uniform load, case 1	Front bolt (4)	261446.7	261172.5	261089.3	260909.3	263608.5
	Dump body bolt (5)	2802732.0	2818412.4	2855024.0	2853162.8	2424200.2
	Actuator mount (6)	223453.1	223223.4	218765.6	222157.8	233909.5
Non-uniform load, case 2	Front bolt (7)	246041.6	245418.6	245683.3	245485.6	247841.9
	Dump body bolt (8)	2693055.0	2661307.2	2727617.0	2602322.0	2349900.2
	Actuator mount (9)	208122.4	207986.9	209591.8	207556.7	217715.4
Non-uniform load, case 3	Front bolt (10)	240114.7	239861.4	239176.5	239860.6	241910.8
	Dump body bolt (11)	3118629.0	3121793.7	3145833.0	3110604.7	2746970.7
	Actuator mount (12)	199574.7	199509.3	199464.1	198733.6	209959.4

a) 

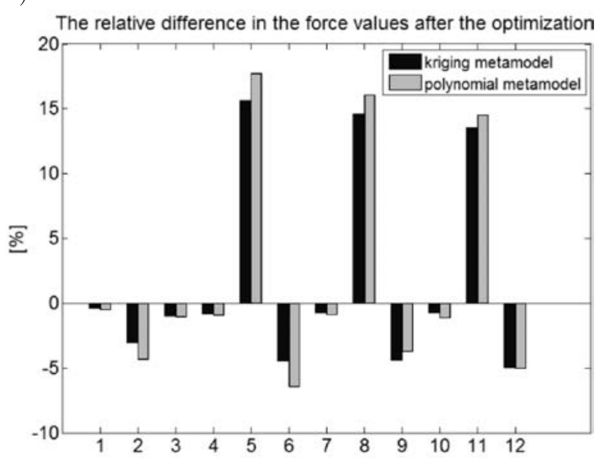
b) 

Fig. 13. The comparison of the results obtained by utilization of Kriging and polynomial regression metamodels; a) relative differences between predictions and numerical results, b) changes in measured forces after applying new k and α coefficients.

The tabular results show the predicted optimal values and the simulation values with optimal ik and $i\alpha$. The graph on the left – percentage differences between the results from Table 4 (columns 1–4). The graph on the right – the comparison of the force values before and after the optimization process, for the optimal values from both metamodels (columns 2, 4, 5 in Table 4).

8. Conclusions

Minimization of the forces acting on a kingpin and an actuator mount point have proved to be successful however the forces in dump body bolt have been reduced only for the uniform load case. Therefore, the target of the optimization has been partially achieved. The increase of the last force value is significant and its correlation with the response surface depends on the metamodeling technique and varies from 15 to 17% for the first type of non-uniform load case and 14 to 16% and 13 to 15% for the rest of examined cases. The situation is caused by the inverted orientation of the constructed surrogates slopes, what introduces the competitive objectives in the optimization process When the forces at the front of the construction are minimized, the force in the rear bolt grows. That leads to the conclusion, that parameters of suspension components are well designed and there is no need of changing them. Nevertheless, if the strong need of reducing force values at the front of the construction arises it can be accomplished by applying the values obtained from the presented optimization procedure In such a case, however, the strengthening of the dump body bold construction is recommended, because of the highly disadvantageous influence of the non-uniform cargo arrangement.

Changing weights in the desirability function may result in reducing the forces in the area mentioned above, however it will increase loads in the other two crucial points, due to the trend of their responses.

It has been shown that fitting and prediction of the interpolated values have been done with high accuracy, what has been confirmed by a single configurations examination (Fig. 12) The comparison of both metamodeling methods has led to the estimation of divergence between them and experimental data. Based on that information, it is possible to state that Kriging technique is more robust and provides more accuracy than polynomial regression.

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