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One-at-a-Time Sensitivity Study of a Nonlinear Fire Truck Suspension Model

In this paper the detailed OAT (one-at-a-time) sensitivity analysis of a nonlinear fire truck suspension system is carried out with numerical simulation. As output to measure sensitivity the RMS of acceleration was chosen, which can be calculated with numerical simulations easily. The degree of sensitivity was measured with a sensitivity index and based on it sensitivity Fuzzy-sets were established. The membership of each parameter to the Fuzzy sets is calculated and based on it, it was determined which parameters are the most sensitive. With the presented results it is shown that the proposed method is suitable for testing mathematical models as well.

Keywords: *sensitivity analysis, fire truck suspension, numerical simulation, nonlinear system modelling, Fuzzy sets,*

1. INTRODUCTION

Parameter sensitivity analysis is used in several fields of science, for example economy [1], environmental engineering [2]-[5], chemistry [6], manufacturing [7],8]. Nowadays the use of sensitivity analysis is spreading in mechanical and vehicle engineering too [9]-13].

Sensitivity analysis is mostly used to find out how the change in parameters affect the systems behaviour [14]. Parameter identification [15] and inverse simulation [16] tasks can also be solved by sensitivity study.

Previously the One-at-a-Time (OAT) parameter sensitivity study of a Duffing-type semi-active suspension system was carried out [17], where it was observed that the damping coefficient is the most sensitive parameter. A simple output parameter was chosen and based on it sensitivity Fuzzy sets were established to reflect the degree of sensitivity. To continue our research we have moved to a more complex mechanical system, which is a nonlinear fire truck suspension system. The aim of this study is to examine which parameters are sensitive from the point of view of the superstructure.

This paper is organised as follows: first the Sensitivity Index and Fuzzy sets are determined to measure the sensitivity of the parameters. Next the mathematical model of the fire truck suspension is described, which is followed by the results of the sensitivity study. The paper concludes with summary of results and further research tasks.

2. PARAMETER SENSITIVITY STUDY METHOD

Sensitivity can be measured with the change of a selected output parameter. In this study the RMS (root mean square) of the acceleration was chosen, because it is widely used in vibration measurements [18]. The acceleration of the superstructure was examined because in case of firefighting the carried equipment is the most important to protect. The RMS of the acceleration can be calculated by the following formula [19]:

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} a_i^2}{n}} \tag{1}$$

where a_i is the acceleration value at i_{th} time and n is the number of acceleration values. Numerical simulations were carried out with Maple. *ODE45* numerical solver was used with 0.01 step size and the maximum time was 50 s.

One percent change in the original parameter was examined in a wide range (1%-200%). The parameter is considered sensitive, when a small change (1%) in a parameter changes the RMS value rapidly. Sensitivity is expressed with Sensitivity Index (SI), which can be calculated as the ratio between the relative change in RMS and the relative change in the selected parameter [4]:

$$SI = \frac{change\,in\,RMS\ \ [\%]}{change\,in\,parameter\ [1\%]} \tag{2}$$

The following Fuzzy sets and membership functions [20]-[21] were established depending on the sensitivity index based on the simulation results of [17]:

1. not sensitive: SI<=0.1
2. moderately sensitive: 0.1<SI<=0.6
3. sensitive: 0.6<SI<2
4. extremely sensitive: 2<SI

In this study it is examined that in the selected range, which parameters are the most sensitive, which means which parameter has the largest membership rate in Fuzzy set 4.

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3. NONLINEAR FIRE TRUCK SUSPENSION MODEL

Our model is based on a Hungarian heavy-duty fire truck Csepel CSD-755-10. The vehicle and its suspension can be seen in Figure 1.

Figure 1. Csepel CSD-755-10 fire truck and its suspension system

The half vehicle model of the suspension used for numerical simulations can be seen in Figure 2. A more detailed description about the fire truck and the development of the simulation model is described in [22].

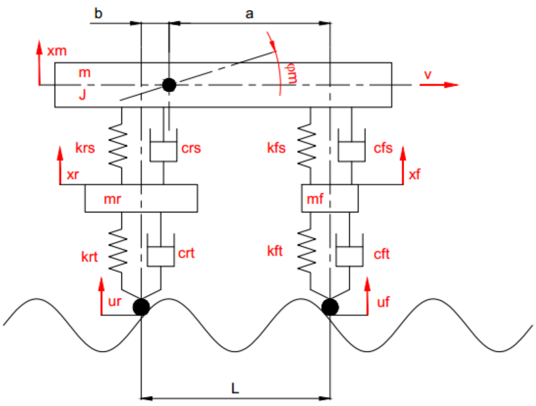

Figure 2. Half-vehicle model of the suspension

The equations describing the systems behaviour are

$$m\ddot{x}_m = F_{ksr} + F_{csr} + F_{ksl} + F_{csl} \tag{3}$$

$$J\ddot{\varphi} = \left(F_{ksr} + F_{csr}\right)b + \left(F_{ksl} + F_{csl}\right)a \tag{4}$$

$$m_r\ddot{x}_r = -F_{ksr} - F_{csr} + F_{ktr} + F_{ctr} \tag{5}$$

$$m_f\ddot{x}_f = -F_{ksf} - F_{csf} + F_{ktf} + F_{ctf} \tag{6}$$

The force applied by the tire and the force applied by the suspension leaf spring are approximated by the following nonlinear equation. The tire is modelled by a similar nonlinear spring with a smaller nonlinear coefficient [23].

$$F_{ki} = k_i \cdot \operatorname{sgn}\left(\Delta u_{ij}\right)\left|\Delta u_{ij}\right|^{n_i} \tag{7}$$

The damping force of the shock absorbers is approximated by the following equation [24].

$$F_{ki} = k_i \cdot \operatorname{sgn}\left(\Delta u_{ij}\right)\left|\Delta u_{ij}\right|^{n_i} \tag{8}$$

The damping effect of the tire was modelled as a linear damper [23].

The relative displacement are:

$$\Delta u_{mfs} = x_m - x_f - \varphi a \tag{9}$$

$$\Delta u_{mrs} = x_m - x_r + \varphi b \tag{10}$$

$$\Delta u_{fst} = x_f - u_f \tag{11}$$

$$\Delta u_{rst} = x_r - u_r \tag{12}$$

The initial parameters for the sensitivity study are summarized in Table 1 [22],[25],[26].

The road profile was assumed to be sinusoidal:

$$u_f\left(t\right) = A \cdot \sin\left(\frac{2\pi v}{\lambda} t\right) \tag{13}$$

$$u_r\left(t\right) = A \cdot \sin\left(\frac{2\pi v}{\lambda}\left(t - T_d\right)\right) \tag{14}$$

where T_d is the time delay between the front and rear tire and is expressed by the following equation:

$$T_d = \frac{L}{v} \tag{15}$$

Table 1. Initial simulation parameters

Name	Param.	Value	Unit
mass of the front axle	m_f	310	kg
mass of the rear axle	m_r	740	kg
mass of the superstructure	m	7200	kg
moment of inertia	J	28600	kgm^2
front suspension spring coefficient	k_{fs}	300000	N/m
rear suspension spring coefficient	k_{rs}	400000	N/m
front suspension damping coefficient	c_{fs}	20000	Ns/m
rear suspension spring coefficient	c_{rs}	40000	Ns/m
front tire spring coefficient	k_{ft}	1000000	N/m
front tire spring coefficient	k_{rt}	1800000	N/m
front tire damping coefficient	c_{ft}	500	Ns/m
front tire damping coefficient	c_{rt}	1000	Ns/m
distance between front axle and center of mass	a	3.486	m
distance between rear axle and center of mass	b	0.613	m
front suspension spring nonlinear coefficient	s_{fs}	1.3	
rear suspension spring nonlinear coefficient	s_{rs}	1.45	
front suspension damper nonlinear coefficient	d_{sf}	2.2	
rear suspension damper nonlinear coefficient	d_{sr}	2.2	
front tire nonlinear coefficient	s_{ft}	1.1	
rear tire nonlinear coefficient	s_{rt}	1.1	

4. OAT SENSITIVITY STUDY OF A FIRE TRUCK SUSPENSION

4.1 Mass and moment of inertia

In Figure 3 the sensitivity of the mass parameters can be seen. The mass of the superstructure is extremely sensitive, when it's low (m <1500 kg) with SI=4.28. The range between 1500<m<2200 kg is sensitive with SI =0.72 and when 2200<m kg it is moderately sensitive with SI=0.21. The moment of inertia and the mass of the front and rear axles are not sensitive, the maximum value of their Sensitivity index is 0.032, 0 and 0.003 respectively. To summarize from the mass parameters only the mass of the superstructure is sensitive, but only at low values. The mass of the superstructure cannot be reduced below a certain limit, therefore this configuration won't occur in reality.

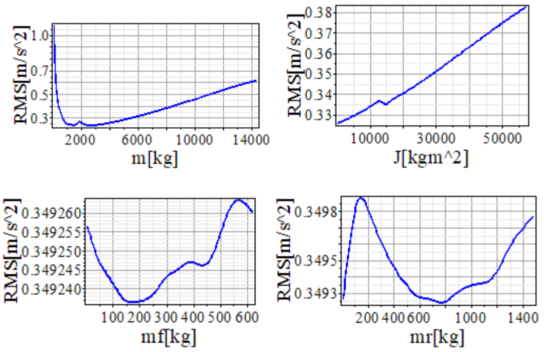

Figure 3. Sensitivity of the mass parameters (above left: mass of the vehicle, above right: moment of inertia, below left: mass of front axle, below right: mass of rear axle)

4.2 Spring coefficients

In Figure 4 the sensitivity of the spring coefficients can be seen. The spring stiffness of the front axle suspension is sensitive, when 517000<k_{fs}<520000 N/m with SI=0.7 and is moderately sensitive, when 30000<k_{fs}<50000 N/m with SI=0.57. In all the other ranges this parameter is not sensitive. The spring stiffness of the rear axle suspension is sensitive, when 150000<k_{rs}<250000 N/m with SI=1.4 and moderately sensitive, when 70000 <k_{rs}<150000 N/m with SI=0.3. This parameter is not sensitive in other parameter ranges. The stiffness of the front tire is not sensitive, except when it's low (k_{ft}<30000 N/m with SI=0.75).

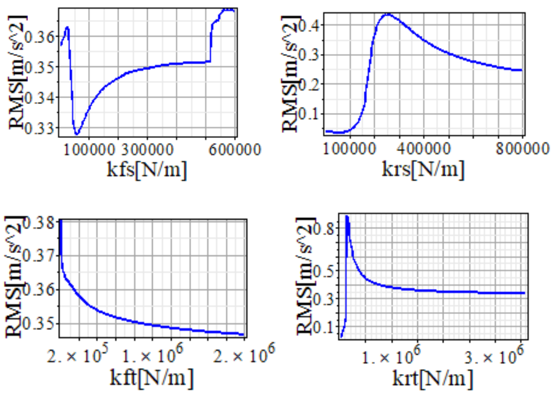

Figure 4. Sensitivity of the spring coefficients (above left: front axle suspension, above right: rear axle suspension, below left: front tire, below right: rear tire)

The stiffness of the rear tire is extremely sensitive, when it's low value (k_{rt}< 140000 N/m) and is sensitive, when 140000< k_{rt}< 800000 N/m (SI=1.39). When k_{rt} is further increased it will be not sensitive. To summarize the spring stiffness parameters are sensitive in low value ranges, in case of higher values they are not sensitive. These parameters are more sensitive in case of the rear axle suspension, as the SI value is higher. The rear axle suspension stiffness can be extremely sensitive in case of low values.

4.3 Damping coefficients

In Figure 5 the sensitivity of the damping coefficients can be seen. The damping coefficients of the tires is not sensitive. It is also confirmed by the literature as the damping effect of the tire is often neglected in simulation models [28]-[30]. Surprisingly the damping coefficient of the shock absorbers are also not sensitive, only the damping coefficient of the rear shock absorber is moderately sensitive in case of low values (c_{fs}<15000 Ns/m with SI=0.175)

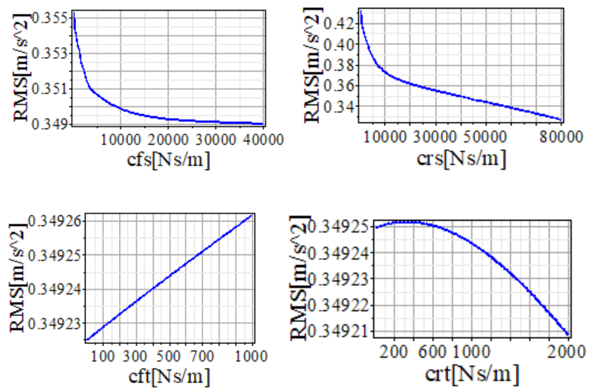

Figure 5. Sensitivity of the damping coefficients (above left: front axle suspension, above right: rear axle suspension, below left: front tire, below right: rear tire)

4.4 Longitudinal distances

In Figure 6 the sensitivity of the longitudinal distances can be seen. The distance between the front axle and centre of mass (a) is sensitive, when 1.5<a<1.9 m and is moderately sensitive, when 0.5<a<1.5 m. In other ranges it is not sensitive. This parameter is not sensitive in the range of its initial value (a=3.486 m). It is a good result as because manufacturing tolerances won't affect the system's behaviour. The distance between the rear axle and the centre of mass (b) is moderately sensitive in the whole test range and changes almost linearly as parameter b is varied. It means that during manufacturing this parameter needs a stricter tolerance.

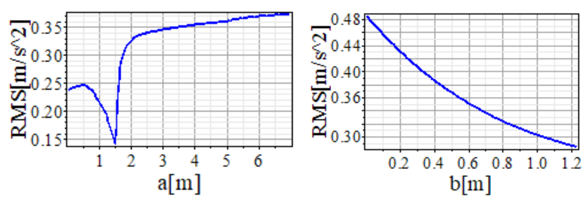

Figure 6. Sensitivity of the longitudinal distances (left: front axle-cenre of mass, right: rear axle-centre of mass)

4.5 Nonlinear coefficients

In Figure 7 the sensitivity of the nonlinear coefficients can be seen. In case of low parameter values (<0.6) singularity occurred during simulation, therefore these parameters were examined from around from 30%-60%

to 200%. The nonlinear coefficient of the front suspension spring is extremely sensitive, when $s_{fs}<1$. The RMS values also oscillate. It means that the proposed nonlinear spring model is not suitable in case of degressive spring characteristics. This parameter is moderately sensitive, when $1<s_{fs}<2.05$ and is not sensitive, when $2.05<s_{fs}$. The nonlinear coefficient of the rear suspension spring is extremely sensitive, when $0.75<s_{rs}<0.95$ and $1.6<s_{rs}<1.8$. It is sensitive, when $0.95<s_{rs}<1.6$ and is not sensitive at all when $1.8<s_{rs}$. To summarize it is advised to use springs with progressive characteristics. The sensitivity of the leaf spring characteristics will be further examined in the future comparing other spring models as well and laboratory measurements. Surpsrisingly the nonlinear coefficient of the shock absorbers is not sensitive in the test range, only the nonlinear coefficient of the rear shock absorber is moderately sensitive when $1<d_{rs}<1.8$. It can be stated that this parameter is more sensitive in the case of the rear axle suspension, so a more accurate shock absorver model is necessary in the case of the rear axle. The nonliear coeffcient of the front tire is not sensitive, but suprisingly the nonlinear coefficient of the rear tire is moderately sensitive in all test range except $1.83<s_{rt}<1.83$, where it is extremely sensitive. It can be stated from the simulation results and the scientific literature that the nonlinear effect of the tires cannot be negleted in vehicle simulations. It can also be concluded that this test will be most likely suitable to test the accuracy and applicability of spring and shock absorber models in vehicle simulations.

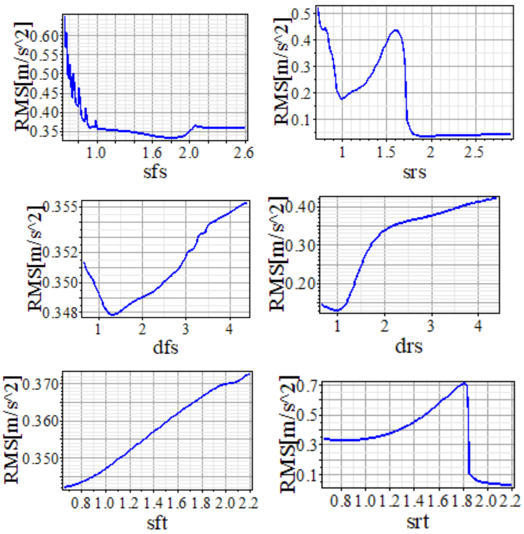

Figure 7. Sensitivity of the nonlinear coefficients (above left: front suspension spring, above right: rear suspension spring, middle left: front shock absorber, middle right: rear shock absorber, below left: front tire, below right: rear tire)

4.6 Road parameters

In Figure 8 the sensitivity of the road parameters can be seen. The wavelength of the road is extremely sensitive in case of low values ($\lambda<7$ m). In the case of this test range there are oscillations similar to parameter s_{fs}. This parameter has the highest SI value also (SI=220). Further study is necessary to obtain the cause of it and the oscillations also. In the other test ranges this parameter is either sensitive or moderately sensitive, there is no range, when it is not sensitive.

The amplitude of the road is extremely sensitive when $0.0024<A<0.0026$ m with SI=10, all the other test ranges it is moderately sensitive. These are input parameters, therefore they cannot be controlled from the vehicle. In the future other (e.g. stochastic and measured) road profiles will be tested as well.

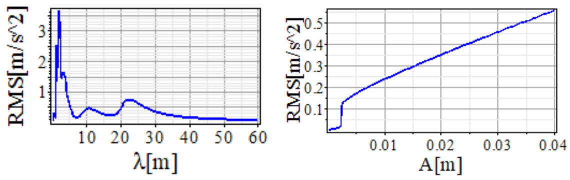

Figure 8. Sensitivity of the road parameters (left: wavelength, right: amplitude)

4.7 Vehicle speed

In Figure 9 the sensitivity of the vehicle speed can be seen. The speed of the vehicle is extremely sensitive when $66<v<77$ km/h with SI=2.5 and it is sensitive when $30<v<66$ km/h. All the other test ranges it is moderately sensitive or not sensitive. The sensitive range is the case of travelling on a carriageway with a speed limit of 90 km/h and an urban road with a speed limit of 50 km/h. It can be concluded that in the case of undulated road the speed of the vehicle should be chosen carefully. In the future the sensitivity of the vehicle speed will be examined with other road profiles as well.

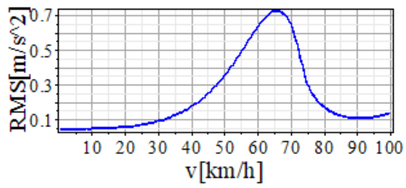

Figure 9. Sensitivity of vehicle speed

4.8 Group parameters into Fuzzy sets

Table 2 summarizes the results. The percentage of the membership of the established Fuzzy sets is showed for each examined parameter.

It can be seen that the following parameters are not sensitive at all, as their membership in Fuzzy set 1 is 1: front axle mass (m_f), rear axle mass (m_r), moment of inertia (J), most damping coefficients (c_{fs}, c_{ft}, c_{rt}), nonlinear coefficient of the front shock absorber (d_{fs}) and tire (s_{ft}). The following parameters are also not sensitive in most of the test range, but there are certain values, where they are moderately sensitive or sensitive: damping coefficient of the rear shock absorber (c_{rs}), the spring coefficients (k_{fs}, k_{rs}, k_{ft}, k_{rt}), nonlinear coefficient of the rear shock absorber (c_{rs}), the distance between the front axle and the centre of mass (a) and nonlinear coefficient of the rear shock absorber (d_{rs}). From these parameters the spring stiffness of the rear tire (k_{rt}) is extremely sensitive in a small range (membership in Fuzzy set 4 is 0.02). The nonlinear coefficient of the front leaf spring (s_{fs}) is also extremely sensitive, but in a higher range (membership in Fuzzy set 4 is 0.17).

Table 2. Membership of the parameters to the Fuzzy sets

Parameter	SI (worst)	Fuzzy 1	Fuzzy 2	Fuzzy 3	Fuzzy 4
m	4,28	0	0.85	0.05	0.1
m_f	0	1	0	0	0
m_r	0.003	1	0	0	0
J	0.028	1	0	0	0
k_{fs}	0.7	0.96	0.035	0.005	0
k_{rs}	1.4	0.77	0.1	0.13	0
k_{ft}	0.75	0.99	0	0.01	0
k_{rt}	12,98	0.78	0	0.18	0.04
c_{fs}	0,019	1	0	0	0
c_{rs}	0,17	0.82	0.18	0	0
c_{ft}	0	1	0	0	0
c_{rt}	0	1	0	0	0
a	1,65	0.8	0.14	0.06	0
b	0,1	0	1	0	0
s_{fs}	7.8	0.705	0.125	0	0.17
s_{rs}	2.9	0	0	0.3	0.7
d_{fs}	0,012	1	0	0	0
d_{rs}	0,55	0.79	0.21	0	0
s_{ft}	0,022	1	0	0	0
s_{rt}	22	0	0.98	0	0.02
λ	135	0	0.64	0.18	0.18
v	2.5	0.3	0.23	0.36	0.11
A	10	0	0.995	0	0.005

The following parameters are considered moderately sensitive, because their membership in Fuzzy set 2 has the highest value: mass of the superstructure (m), distance between the rear axle and the centre of mass (b), nonlinear coefficient of the rear tire (s_{rt}), wavelength of the road (λ) and amplitude of the road (A). Except parameter b all of these parameters have a range where they are sensitive or extremely sensitive. All of their membership in Fuzzy set 4 is above 0.1, therefore special attention is necessary in these ranges.

The speed of the vehicle is considered sensitive, its membership in Fuzzy set 3 is 0.36. It is an interesting parameter, as it is the only one, which has membership in all Fuzzy sets. It means that the sensitivity of this parameters varies all over the test range, therefore it should be tested in detail in other parameter configurations as well.

The nonlinear coefficient of the rear suspension spring is extremely sensitive. It has the highest membership in Fuzzy set 4 (0.7), therefore it is the most sensitive parameter. With this result it can be also stated, that in vehicle simulations it is very important to choose accurate spring and tire models.

5. CONCLUSION

In this paper, the detailed OAT sensitivity analysis of a nonlinear fire truck suspension system is carried out with numerical simulation. The degree of sensitivity was observed with the membership of four separate sensitivity Fuzzy sets. It was examined that the nonlinear coefficient of the rear suspension spring was the most sensitive parameter. With this result it is shown that accurate spring and tire models are necessary in vehicle simulations. The speed of the vehicle was also sensitive. A lot of parameters have ranges, where they are extremely sensitive or sensitive. These ranges should pay special attention during the design and development process. With the presented results it was shown that the proposed method is not only suitable for sensitivity analysis of parameters, but that the accuracy of a mathematical model can also be tested. Further research tasks are to extend the presented method to other engineering applications as well and to develop the mathematical model of the fire truck suspension with more accurate spring, shock absorber and road models.

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ИСТРАЖИВАЊЕ ОСЕТЉИВОСТИ ЕЛЕМЕНАТА НЕЛИНЕАРНОГ МОДЕЛА ОГИБЉЕЊА ВАТРОГАСНОГ КАМИОНА

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Рад се бави детаљном анализом осетљивости сваког појединачног елемента нелинерног система огибљења ватрогасног камиона применом нумеричке симулације. Средња вредност квадрата је изабрана за излаз мерења осетљивости која се може лако измерити нумеричком симулацијом. Степен осетљивости је мерен индексом осетљивости и на основу њега су одређени фази скупови осетљивости. Сваки параметар обухваћен фази скупом је израчунат и утврђено је који су параметри најосетљивији. Добијени резултати показују да је предложени метод погодан и за испитивање математичких модела.