IARJSET

ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Vol. 6, Issue 5, May 2019

Development of a simulation model for analyzing vibrations of a double cabin fire truck and their effects on firefighters

Flóra Hajdu [1], Rajmund Kuti [1]

Department of Mechatronics and Machine Design, Faculty of Mechanical Engineering, Informatics and Electrical Engineering, Széchenyi István University, Győr, Hungary[1]

Abstract: Various vibrations occur in vehicles, which are generated by the vehicle's equipment or by the road itself. Several studies have been carried out on the investigation of vibrations in passenger cars or different purpose trucks, but there is little literature available on the analysis of special superstructure vehicles such as fire trucks. During our research therefore a simulation model for analyzing the vibrations of a double-cabin special fire truck was created. The main purpose of our research is investigating their effects on people traveling in fire-fighting vehicles. In this paper the developed model and the computer simulation using it is presented. With our results we want to draw the attention to the importance of the topic and to help the safe operation of fire-fighting vehicles.

Keywords: Double cabin fire truck, firefighter crew, vibrations, numerical simulation

I. INTRODUCTION

Various vibrations occur during operation of machines [1] and vehicles [2], which have an impact on the equipment itself and on the operator [3] or the person driving or traveling in it [4]. Scientific research on the resulting vibrations and their effects is an important task, since harmful vibrations can cause serious health problems [5]-[6]. The drivers of fire trucks and the on-board firefighter crew are also subject to increased load. Driving at the highest possible speed to the locations of fires or accidents is a heavy burden on both the vehicle and the crew [7]. Most of the literature deals with the vibrations on people driving or traveling in passenger cars [8]-[10] or trucks [11]-[13]. The effects of vibrations on people traveling on special vehicles including fire trucks them has not yet been investigated. In this paper the mathematical modeling and numerical simulation of a MB RB TLF 2000 double-cabin fire truck is presented. The model was developed in order to examine the vibrations on the firefighter crew.

II. TECHNICAL PARAMETERS OF THE TESTED VEHICLE

The vehicle chosen for our research is a mid-range fire truck with an Austrian-built Rosenbauer superstructure built on a German Mercedes-Benz 1124 chassis. The vehicle has a ladder frame with rigid front and rear axles. The vehicle is all-wheel drive with lockable tranfer gear. Both axles are equipped with leaf springs and an auxiliary leaf spring for permanent load is installed at the rear axle. Hydraulic shock absorbers on both sides provide the proper road holding. The vehicle is powered by a 117 kW Mercedes-Benz OM366LA-Euro II. refueling four-stroke diesel engine that drives the RB-NH30 type 2+2 step fire pump through a separate drive. The vehicle was equipped with a special fire truck superstructure, including the 4-person crew compartment. The special fire fighting equipment, which contains the 2000-liter water tank and the 200-liter foam tank, as well as the 2400 liter / min water/foam pump and the storage compartments for fire-fighting equipment and hoses are also built in the superstructure. The superstructure is fixed with a separate subframe to the vehicle chassis. The 125-liter fuel tank is fixed on the right, the battery compartment on the left to the superstructure. The driver's cabin is 2-person, tiltable, detached from the superstructure and secured to the main chassis with special rubber mount. The rear of the cabin and the front part of the crew compartment were cut to provide a common space. There is a special rubber seal between the cabin and the crew compartment, which ensures the movement of the parts, while sealing the surfaces. The vehicle is equipped with a 6 + 1-speed synchronous transmission unit, with a top speed of 110 km / h according to manufacturer’s catalogue.

The structure of the vehicle is showed in Fig 1 and in Table I.

IARJSET

ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Vol. 6, Issue 5, May 2019

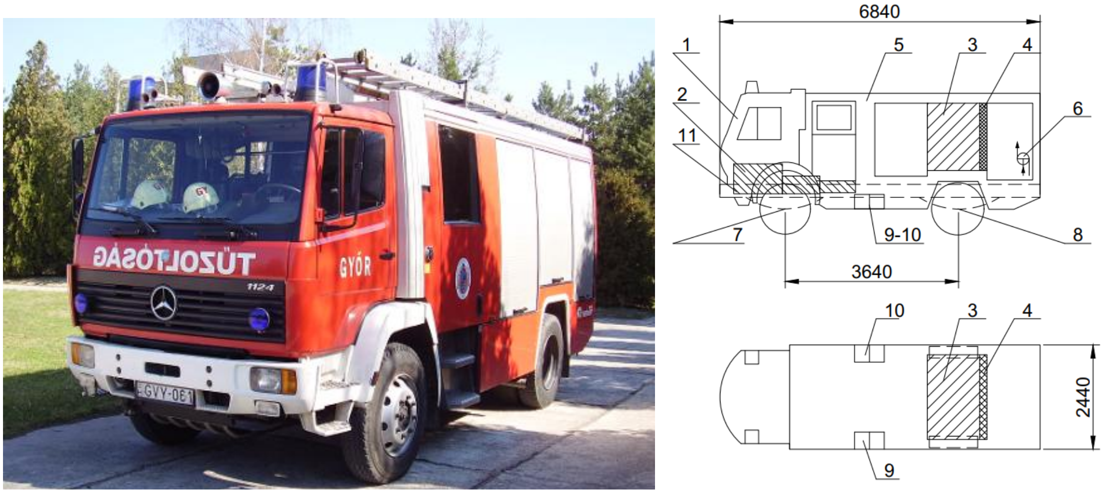

Fig 1. MB RB TLF 2000 fire truck (the length and width dimensions of the vehicle are in mm)

TABLE I. MASS PARAMETERS (BASED OR MANUFACTURERS CATALOGUE)

Title number	Name	Mass [kg]
1	Cabin	450
2	Engine + transmission	2400
3	Water tank (2000 l)	2200
4	Foam tank 200 l)	225
5	Superstructure (crew compartment + equipment)	4130
6	Pump	240
7	Front axle	450
8	Rear axle	670
9	Battery	100
10	Fuel tank	135
11	Chassis	2500
		Σ 13500

III. MODEL OF THE DOUBLE CABIN FIRE TRUCK SUSPENSION

The model was based on the half-vehicle model developed in [14]. It was expanded with additional elements, like cabin and superstructure separated from the chassis. The driver seat was modelled as an additional mass-spring-damper system [15]. The model can be seen in Fig 2.

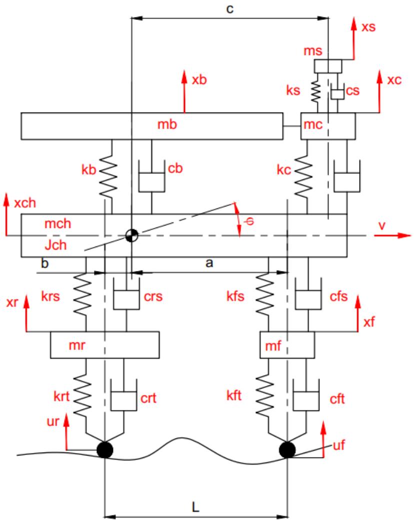

Fig. 2. Dynamic model of the vehicle

 DOI 10.17148/IARJSET.2019.6511

IARJSET

ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Vol. 6, Issue 5, May 2019

The equations of motion describing the system's dynamics can be obtained with free-body diagrams [16][16].

The equations describing the suspension's behavior

$$m_s\ddot{x}_s = F_{ks} + F_{cs} \tag{1}$$
$$m_c\ddot{x}_c = -F_{ks} - F_{cs} + F_{kc} + F_{cc} \tag{2}$$
$$m_c\ddot{x}_c = -F_{ks} - F_{cs} + F_{kc} + F_{cc} \tag{3}$$
$$m_b\ddot{x}_b = F_{kb} + F_{cb} \tag{4}$$
$$m\ddot{x}_{ch} = -F_{kc} - F_{cc} - F_{kb} - F_{cb} + F_{ksr} + F_{csr} + F_{ksl} + F_{csl} \tag{5}$$
$$J\ddot{\varphi} = -(F_{kc} + F_{cc})c + (F_{ksr} + F_{csr})b + (F_{ksl} + F_{csl})a \tag{6}$$
$$m_r\ddot{x}_r = -F_{ksr} - F_{csr} + F_{ktr} + F_{ctr} \tag{7}$$
$$m_f\ddot{x}_f = -F_{ksf} - F_{csf} + F_{ktf} + F_{ctf} \tag{8}$$

The rubber mount was modeled as a simple, commonly used Kelvin-Voigt model that consists of a spring and a damper coupled in parallel [17]. The rubber mount of the cabin and the seat suspensions were modelled as a linear spring and damper. The damping effect of the tire was also modelled as a linear damper.

$$F_{ki} = k_i\Delta u_{ij} \tag{9}$$
$$F_{ci} = c_i\Delta\dot{u}_{ij} \tag{10}$$

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 equation [15].

$$F_{ki} = k_i \cdot sgn(\Delta u_{ij})\left|\Delta u_{ij}\right|^{n_i} \tag{11}$$

The damping force of the shock absorbers is approximated by the following equation [15].

$$F_{ci} = c_i \cdot sgn(\Delta\dot{u}_{ij})\left|\Delta\dot{u}_{ij}\right|^{n_i} \tag{12}$$

The relative displacement are

$$\Delta u_{sc} = x_s - x_c \tag{13}$$
$$\Delta u_{chb} = x_b - x_{ch} \tag{14}$$
$$\Delta u_{chc} = x_c - x_m + \varphi c \tag{15}$$
$$\Delta u_{chfs} = x_m - x_f - \varphi a \tag{16}$$
$$\Delta u_{chrs} = x_m - x_r + \varphi b \tag{17}$$
$$\Delta u_{fst} = x_f - u_f \tag{18}$$
$$\Delta u_{rst} = x_r - u_r \tag{19}$$

The mass parameters of the vehicle were taken from manufacturer's catalog. The parameters of spring stiffness and the damping coefficients were taken from literature [19]-[22]. The parameters used for simulation are listed in Table II.

TABLE II. PARAMETERS USED FOR SIMULATION

Name	Notation	Value	Unit
mass of seat + firefighter	m_s	100	kg
mass of cabin	m_c	205	kg
mass of superstructure	m_b	3515	kg
mass of chassis	m_{ch}	2567.5	kg
mass of front suspension	m_f	225	kg
mass of rear suspension	m_r	335	kg
moment of inertia of vehicle body	I_p	26130	kgm^2
rear axle distance from centre of mass	b	0.2	m
front axle distance from centre of mass	a	3.44	m
cabin distance from centre of mass	c	3.5	m
seat spring stiffness	k_s	20000	N/m
cabin rubber mount spring stiffness	k_c	75000	N/m
superstructure rubber mount spring stiffness	k_b	75000	N/m

IARJSET

ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Vol. 6, Issue 5, May 2019

rear suspension spring stiffness	k_{rs}	400000	N/m
front suspension spring stiffness	k_{fs}	300000	N/m
rear tire spring stiffness	k_{rt}	1800000	N/m
front tire spring stiffness	k_{ft}	1000000	N/m
seat damping coefficient	c_s	1000	Ns/m
cabin rubber mount damping coefficient	c_c	7500	Ns/m
superstructure rubber mount damping coefficient	c_b	7500	Ns/m
rear suspension damping coefficient	c_{rs}	40000	Ns/m
front suspension damping coefficient	c_{fs}	20000	Ns/m
rear tire damping coefficient	c_{rt}	1000	Ns/m
front tire damping coefficient	c_{ft}	500	Ns/m
rear suspension spring nonlinear coefficient	n_{krs}	1.45	
front suspension spring nonlinear coefficient	n_{kfs}	1.3	
rear tire spring nonlinear coefficient	n_{krt}	1.1	
front tire spring nonlinear coefficient	n_{kft}	1.1	
rear suspension damping nonlinear coefficient	n_{crs}	2.2	
front suspension damping nonlinear coefficient	n_{cfs}	2.2	

2 different road profiles were used depending on the operation conditions: a motorway with vehicle speed 110 km/h and an urban road with vehicle speed 50 km/h. The motorway and the urban road were modeled as a sinusoidal road profile, which can be described by the following equations:

$$x_f(t) = A \cdot \sin(\omega t) \tag{20}$$

$$x_r(t) = A \cdot \sin(\omega t - T_d \cdot \omega) \tag{21}$$

where ω is the rotational speed, Td is the time delay. Rotational speed depends on the velocity of the vehicle and the wavelength

$$\omega = \frac{2\pi v}{\lambda} \tag{22}$$

The time delay between the front and rear axle is taken into account with the following equation [23]:

$$T_d = \frac{L}{V} \tag{23}$$

The parameters of the different roads are summarized in Table III. [24].

TABLE III. PARAMETERS OF THE ROAD PROFILES

Road type	Wavelength [m]	Amplitude [m]	Vehicle speed [km/h]
motorway	10	0.02	110
urban road	2	0.02	50

The acceleration of the crew compartment can be calculated with the following equation:

$$\boldsymbol{a_{crew}} = \boldsymbol{a_s} + \frac{d}{dt}(\boldsymbol{\omega} x \boldsymbol{r_{crew}}) \tag{24}$$

where a_{crew} is the acceleration at the crew compartment, a_s is the acceleration at the centre of mass, ω is the angular velocity and r_{crew} = 2.5 m is the distance vector.

IV. SIMULATION RESULTS

Numerical simulations were carried out with Maple. *ODE45* numerical algorithm was used for calculations with step 0.01 s [25]. The simulation results can be seen is Fig 3. and Fig 4. In Fig 3. the phase-plane diagrams and the frequency spectrum diagrams of the driver’s seat is shown. In Fig 4. the phase-plane diagrams and the frequency spectrum diagrams of the crew compartment are presented.

IARJSET

ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Vol. 6, Issue 5, May 2019

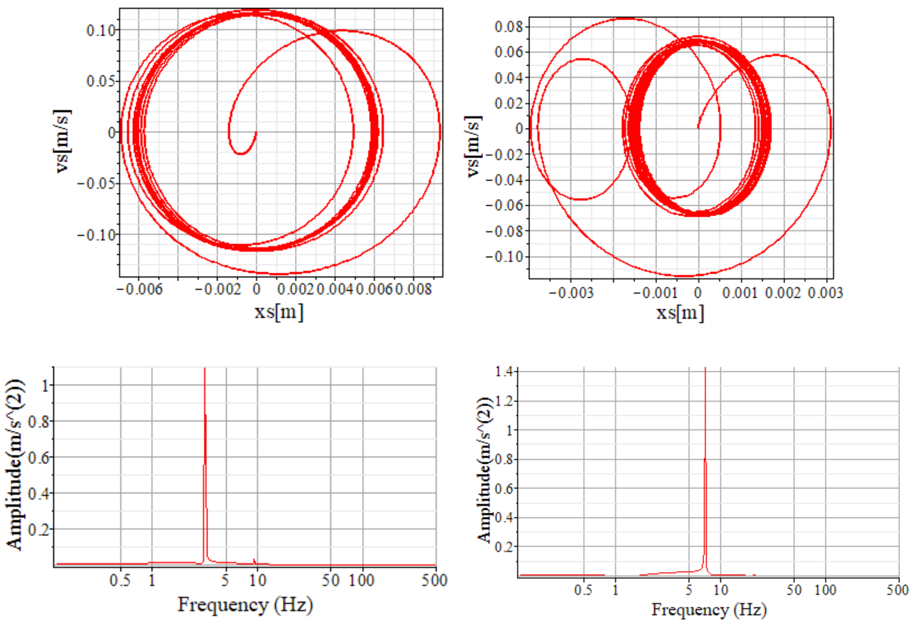

Fig. 3. Phase plane diagram (up) and frequency spectrum diagram (below) of the driver's seat (left: motorway, middle: urban road)

It can be seen int he phase plane diagrams that there is a harmonic vibration. The peak frequency is 3 Hz in case of motorway with 1.1 amplitude. The peak frequency is 7 Hz with 1.4 amplitude in case of urban roads, which exceeds the exposure limit of 8 hours [26]. As the maximum travel time to location of fires and accidents is 25-30 min in Hungary therefore it is not harmful. According to [6] the resulting vibrations are uncomfortable in both cases.

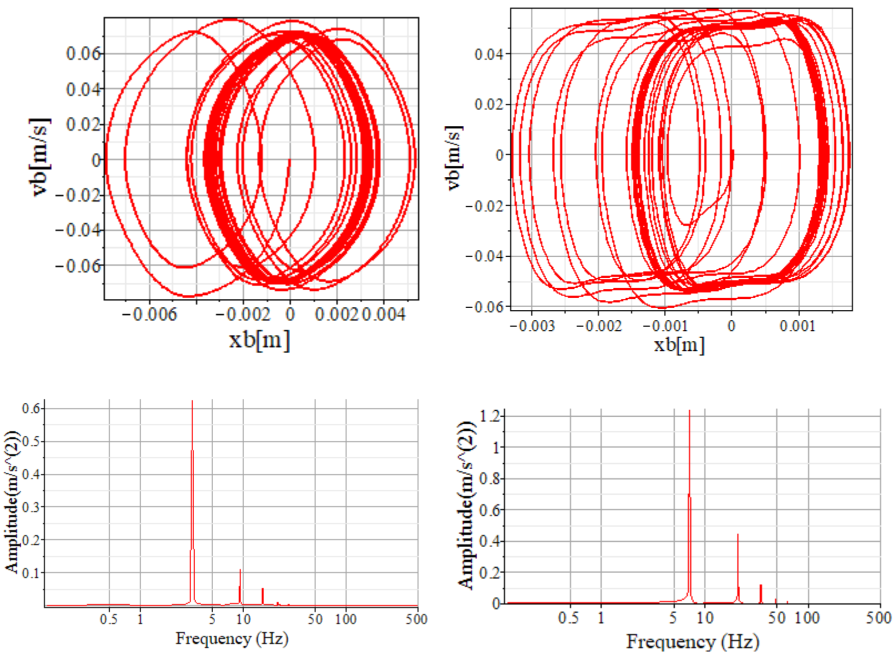

Fig. 4. Phase plane diagram (up) and frequency spectrum diagram (below) of the crew compartment (left: motorway, middle: urban road)

It can be seen in the phase plane diagrams that there is a subharmonic vibration. The peak frequency is 3 Hz in case of motorway with 0.6 amplitude. The peak frequency is 7 Hz with 1.2 amplitude in case of urban roads, which exceeds the exposure limit of 8 hours [26]. As the maximum travel time to location of fires and accidents is 25-30 min in Hungary therefore it is not harmful. According to [6] the resulting vibrations are uncomfortable in case of urban roads.

DOI 10.17148/IARJSET.2019.6511

V. CONCLUSIONS

During our research a simulation model that is suitable for the examination of vibrations of persons traveling in double cabin vehicles with special superstructure was developed. The model was tested with sinusoidal road profiles of a motorway and an urban road. Based on computer simulation it can be concluded that the resulting vibrations are more harmful in case of urban roads. It was also found out that in case of normal condition roads the resulting vibrations in the examined time interval are not harmful, but are uncomfortable to people traveling in them. Next task in our research is to examine the effects of road failures on firefighters and using more precise road profiles. We have come to the conclusion that proper simulation models are essential for results that can be used in practice. We consider it important to develop appropriate models for accurate research on firefighting vehicles as they are essential for exploring the theoretical and practical phenomena and helping to identify further research directions.

ACKNOWLEDGMENT

EMBERI ERŐFORRÁSOK MINISZTÉRIUMA

This study was supported by the ÚNKP-18-3 New National Excellence Program of the Ministry of Human Capacities.

REFERENCES

[1]. G. Stépán, “Delay-differential equation models for machine tool chatter, Dynamics and Chaos in Manufacturing Processes”, Vol. 471152935, pp. 165-192., 1998
[2]. D. Takács, G. Stépán “Contact patch memory of tyres leading to lateral vibrations of four-wheeled vehicles”, Philosophical Transactions of the Royal Society A, Mathematical Physical and Engineering Sciences, Vol. 371, No. 1993, Paper 20120427, p. 12., 2013
[3]. J. Łuczko, P. Cupiał and U. Ferdek, “Regular and Chaotic Vibrations of a Vibration-isolated Hand Grinder, ” Journal of Theoretical and Applied Mechanics, Vol. 45 No. 1, pp. 61-72., 2007
[4]. J. Marzbanrad and A. Keshavarzi, “Chaotic Vibrations of a Nonlinear air Suspension System under Consecutive Half Sine Speed Bump,” Indian Journal of Science & Technology Vol.8 No.3, pp. 72-84, 2015
[5]. K.S.E. Hung, T.T. Chuan and A.L. Ann, “Reducing Vibration in Armoured Tracked Vehicles,” DSTA Horizons, pp. 65-77., 2012
[6]. P. A. Borse and P.S. Desale, “Effect of Motor Vehicle Structural Vibration on Human Body – Review), ” International Advanced Research Journal in Science, Engineering and Technology, Vol. 4 No. 7, pp. 145-149, 2017
[7]. R. Kuti: Rescue vehicles, rescue equipment (in Hungarian), University textbook, Zrínyi Miklós Nemzetvédelmi Egyetem, Budapest, pp. 45, 2007
[8]. R. Burdzik, L. Konieczny, “Vibration issues in passenger car, ” Transport Problems Vol. 9 No. 3, pp. 83-90, 2014
[9]. H. Nahvi, M. H. Fouladi, M. J. M. Nor, “Evaluation of Whole-Body Vibration and Ride Comfort in a Passenger Car”, International Journal of Acoustics and Vibrations Vol. 14 No. 3., pp. 143-149, pp. 2009
[10]. M. Rikaz1 , A. Abeysinghe , M. Perera, “Review on vibration quality improvement of a passenger seat”, Vibroengineering PROCEDIA. Vol. 22., pp. 106-111, 2019
[11]. L. Zhao, C. Zhou, Y. Yu, F. Yang, “A method to evaluate stiffness and damping parameters of cabin suspension system for heavy truck”, Advances in Mechanical Engineering 8(7), pp. 1-9, 2016
[12]. W.J. Evers, I. Besselin, A. Teerhuis, T. Oomen, H. Nijmeijer, “Experimental validation of a quarter truck model using asynchronous measurements with low signal-to-noise ratios”, 10th AVEC conference, Loughborough, UK. 22-26. August, 2010
[13]. O. Stan, D. Iozsa, R. Oprea: “Study concerning the influence of the engine mounting system on the vibration transmissibility to the truck cab”, Recent Advances in Applied Mathematics, Modelling and Simulation, pp. 225-228, 2014
[14]. F. Hajdu and R. Kuti, “Examination of chaotic vibrations during operation of a fire truck”, in Proceedings of MAC 2018 in Prague, pp. 163–170., 2018
[15]. J. Fakhraei, H:M. Khanlo, M. Ghayour, Chaotic behaviors of a ground vehicle oscillating system with passengers”. Scientia Iranica, Vol. 24 No.3, pp. 1051-1068, 2017
[16]. Horváth P., “Basics of Mechatronics II (in Hungarian), ” Széchenyi István University, Győr, Hungary, 2006
[17]. H. Yarmohamadi, “Advances in Heavy Vehicle Dynamics with Focus on Engine Mounts and Individual Front Suspension”, Phd thesis, Chalmers University of Technology, Göteborg, Sweden, supervisor: Viktor Berbyuk, 2012
[18]. Y. Cui, T.R. Kurfess, M. Messman, “Testing and Modeling of Nonlinear Properties of Shock Absorbers for Vehicle Dynamics Studies”, Proceedings of the World Congress on Engineering and Computer Science 2010 Vol II WCECS 2010, October 20-22, 2010, San Francisco, USA, pp. 949-954
[19]. L. Jiao, Vehicle model for tyre-ground contact force evaluation, ” Master thesis, KTH Royal Institute of Technology, 2013
[20]. D. Sekulić, V. Dedović, “The Effect of Stiffness and Damping of the Suspension System Elements on the Optimisation of the Vibrational Behaviour of a Bus” International Journal for Traffic and Transport Engineering (IJTTE). Vol. 1. No. 4. pp. 231-244, 2011
[21]. W.J. Evers, I. Besselin, A. Teerhuis, T. Oomen, H. Nijmeijer, “Experimental validation of a quarter truck model using asynchronous measurements with low signal-to-noise ratios”, 10th AVEC conference, Loughborough, UK. 22-26. August, 2010
[22]. J. Konieczny, J. Kowal, J. Pluta, A. Podsiadlo. “Laboratory research of the controllable hydraulic damper”. Engineering Transactions, Vol. 54 No.3, pp. 203-221., 2006
[23]. R.S. Barbosa, “Vehicle dynamic response due to pavement roughness” Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol. 33 No.3, 2011
[24]. x-engineer.org, “Road profile mathematical modeling for wheel vertical dynamics simulation”, https://x-engineer.org/automotive-engineering/chassis/vertical-dynamics/road-profile-mathematical-modeling-for-wheel-vertical-dynamics-simulation/
[25]. K.L. Vasundhara, “Computer Interface in Euler and Fourth-order Runge - Kutta Method,” International Advanced Research Journal in Science, Engineering and Technology, Vol 4. No. 10, pp. 127-132., 2017
[26]. Encyclopedia of Occupational Health and Safety, http://www.ilocis.org/en/default.html