ROAD FAILURE MEASUREMENT FOR NUMERICAL SIMULATION OF A NONLINEAR FIRE TRUCK SUSPENSION

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Abstract- Road failures can cause damage to vehicles. In case of fire trucks the carried equipment can be damaged too, which can lead to hazardous situations. With numerical simulations the harmful vibrations affecting the vehicle can be determined. In this paper a mathematical model for numerical simulation was established based on Csepel CSD-755-10 fire truck. The suspension of the fire truck was modelled as a mass-spring-damper system. The excitation signal was obtained from the road profile, to which a specific pothole was measured on a poor quality urban road. Simulation was carried out with 3 different vehicle velocities. In this paper it is showed that a pothole with a specific geometric dimension can cause harmful vibrations to the fire truck and the carried equipment.

Keywords- fire truck, road profile measurement, geodetic height measurement, numerical simulation,

I. INTRODUCTION

Road failures like potholes, cracks, undulations can lead to harmful vibrations which can cause damage for both the vehicle and the passenger [[1]]-[[2]]. Road roughness can degrade the handling of the vehicle and lead to malfunction of the vehicle [[3]]. Road failures are the major source of fatigue of vehicle components [[4]]. In addition they reduce driver and passenger comfort too [[5]]. Potholes can cause direct mechanical damage to the vehicle and can lead to break and fatigue of suspension parts [[6]]-[[7]]. In case of fire fighting vehicles road failures can damage both the vehicle and the carried special equipment, which can lead to hazardous situations. In vehicle simulations mostly theoretical or standardized road profiles are used [[8]]-[[12]], but there can be significant difference compared to real road profiles [[13]]. In order to capture vehicle dynamics realistically accurate road profiles are necessary [[14]]-[[15]].

In our previous research we have examined that chaotic vibrations can easily occur during operation of a heavy-duty fire truck in case of an undulated (sinusoidal) road [[15]]. To continue the research the harmful effects of other road failures will be examined. To capture the effects of road failures as accurate as possible detailed road profile measurement was carried out. Our measurement results were implemented to our simulation directly. In this paper the effects of a pothole was examined in simulation environment.

II. ROAD FAILURE MEASUREMENT

To produce the road profile used for excitation first a 3D surface model was created. The shape of the pavement was measured using a Leica Disto S910 digital laser distance gauge to reflect reality as much as possible. Geodetic measurement was used to determine the profile of the road section. The height of the points were measured relative to a starting point. It was assumed that the basic level is the geodit Fig. 1. (metres above the sea level - MASL). Therefore the absolute height of a point is always the MASL of the point and the difference in height between two points is always the difference between MASL of the two points.

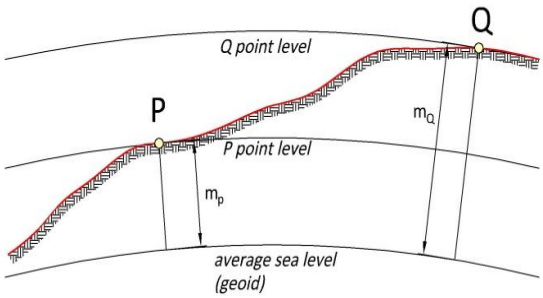


Fig 1. Geodetic height

There are different height measurement methods, of which trigonometric height measurement was used [[18]7]. The applied measurement gauge detects the vertical inclination, measures the direct distance between the gauge and the object, and determines the vertical distance from the horizontal base line by trigonometric calculation. The principle of measurement is shown in Fig 2.

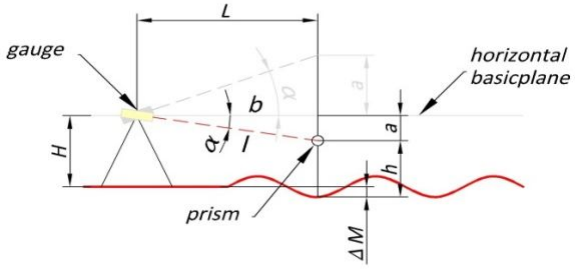


Fig 2. Principle of geodetic height measurement

The vertical distance is calculated with the following formula:

$$a = l \cdot \sin(\alpha) \qquad (1)$$

$$\Delta M = H - h + a \qquad (2)$$

Absolute value a is calculated by the gauge, therefore it will always be a positive number.

There are several road failures, but in this paper the vibrations caused by a pothole is examined. An average pothole is formed by the fragmentation of the upper wear layer of the pavement structure and is usually 5-10cm deep. Such a pothole was digitalized. The density of the measured points is shown in Fig 3.

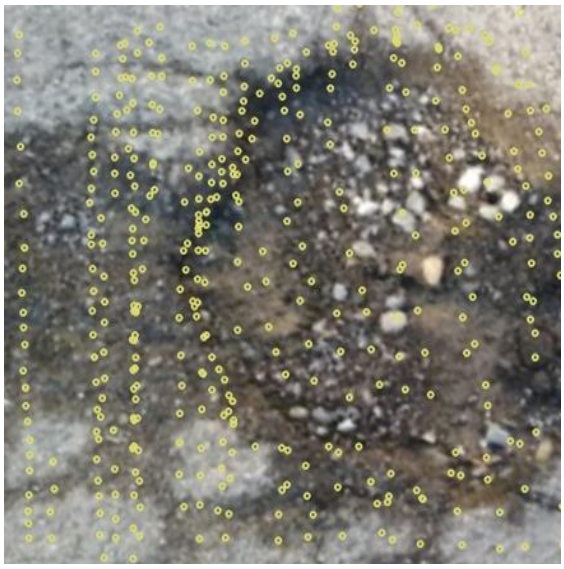


Fig 3. Measured points

The measured points are stored in a dxf file that can be processed with AutoCad later on. A surface model can be created with corrections to make it as close to reality as possible. The surface model is shown in Fig. 4.

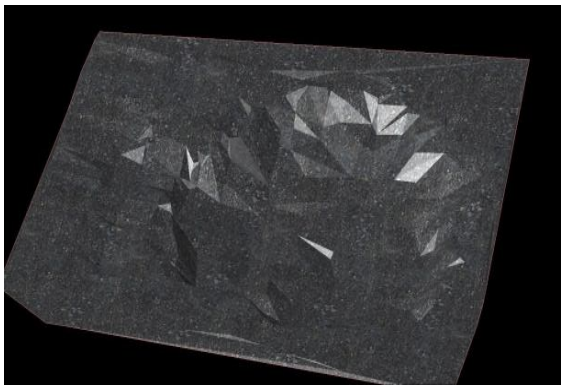


Fig. 4. Surface model of the pothole

From the 3D surface model a 2D cross-section can be created at any plane. The place of the section can be seen in Fig. 5. The 2D profile used for simulations is showed in Fig. 6

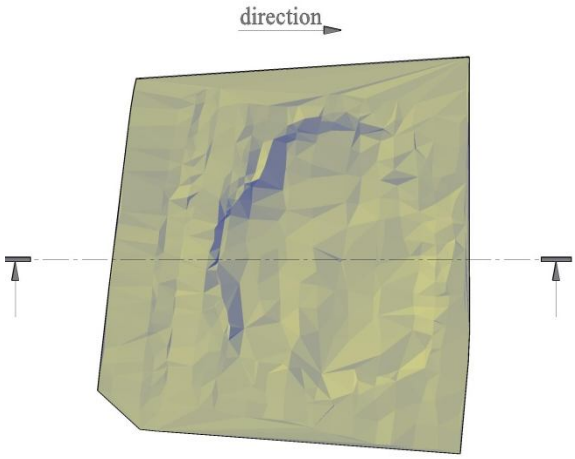


Fig. 5. Place of the section

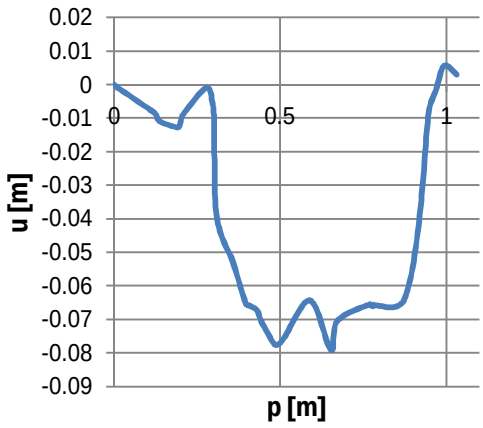


Fig. 6. Measured pothole cross-section

For simulations the displacement of the wheel axis should be considered, which is different from the road profile. The motion curve of the axis was determined with geometrical drafting, taking into the 1100mm diameter of the vehicle wheel into account. For the simulation, this curve was used as excitation (input signal). At first approximation it was assumed that the tires have a single point contact with the road [[18]]. The road profile in the simulation was implemented with a Spline function. The distance was converted into time as a function of speed (Fig. 7) in order to simplify the numerical calculations.

$$t = \frac{p}{v} \qquad (3)$$

where p is the distance covered by the vehicle and v is the speed of the vehicle.

The time delay between the front and rear axle was taken into account with the following equation.

$$T_d = \frac{L}{v} \qquad (4)$$

where L is the distance between the axles (see Fig. 9)

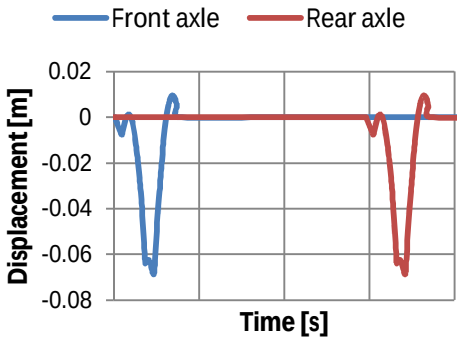


Fig. 7. Input signal for the simulation (50 km/h)

III. SIMULATION

4.1. Suspension model

Our model is based on a Hungarian heavy-duty fire truck Csepel CSD-755-10. The vehicle has a unique design with suspensions with reinforced leaf springs (Fig. 8).



Fig. 8.: Suspension of the fire truck

In firefighting the carried equipment is the most important, therefore to be able to study the vibrations affecting the equipment half-vehicle model has been chosen (Fig. 9).

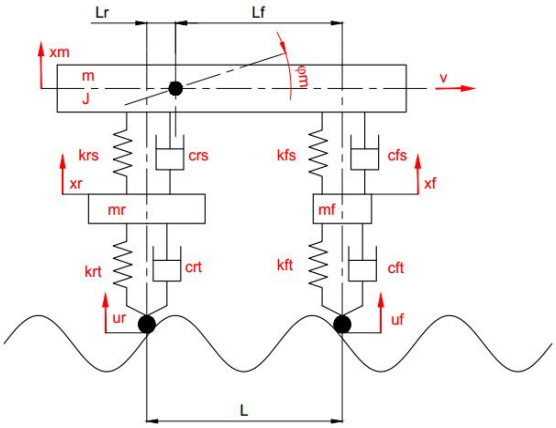


Fig. 9. Suspension model

The equations describing the systems behavior are:

$$m_f \frac{d^2x_f(t)}{dt^2} = F_{kfs} + F_{cfs} + F_{kft} + F_{cft} \quad (5)$$

$$m_r \frac{d^2x_r(t)}{dt^2} = F_{krs} + F_{crs} + F_{krt} + F_{crt} \quad (6)$$

$$m \frac{d^2x_m(t)}{dt^2} = -(F_{kfs} + F_{cfs} + F_{krs} + F_{crs}) \quad (7)$$

$$J \frac{d^2\varphi_m(t)}{dt^2} = bF_{krs} + bF_{crs} + aF_{krt} + aF_{crt} \quad (8)$$

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 exponent.

$$F_{ki} = k_i \cdot \mathrm{sgn}(\Delta u_{ij}) |\Delta u_{ij}|^{n_i} \quad (9)$$

The damping force of the shock absorbers is approximated by the following equation. The damping effect of the tire was assumed to be constant.

$$F_{ci} = c_i \cdot \mathrm{sgn}(\Delta \dot{u}_{ij}) |\Delta \dot{u}_{ij}|^{n_i} \quad (10)$$

The relative displacement are:

$$\Delta u_{mfs} = x_m - x_f - \varphi a \quad (11)$$

$$\Delta u_{mrs} = x_m - x_r + \varphi b \quad (12)$$

$$\Delta u_{fst} = x_f - u_f \quad (13)$$

$$\Delta u_{rst} = x_r - u_r \quad (14)$$

The parameters used for the simulation can be seen in Table 1 [[16]].

Table 1. Simulation parameters

Parameter	Value	Unit
m_f	310	kg
m_r	740	kg
m	5750	kg
m_c	250	kg
m_e	1200	kg
J	28600	kgm^2
k_{fs}	300000	N/m
k_{rs}	400000	N/m
c_{fs}	20000	Ns/m
c_{rs}	40000	Ns/m
k_{ft}	1000000	N/m
k_{rt}	1800000	N/m
c_{ft}	500	Ns/m
c_{rt}	1000	Ns/m
L_r	3.486	m
L_f	0.613	m
L	4.16	m
n_{skf}	1.3	
n_{skr}	1.45	
n_{scf}	2.2	
n_{scr}	2.2	
n_{tkf}	1.1	
n_{tkr}	1.1	

4.2. Simulation results

Urban conditions were examined. The speed of the vehicle was 10 km/h, 30 km/h and 50 km/h. The displacement, the velocity and the acceleration of the superstructure (sprung mass) was calculated with numerical simulations. The results can be seen in the following figures.

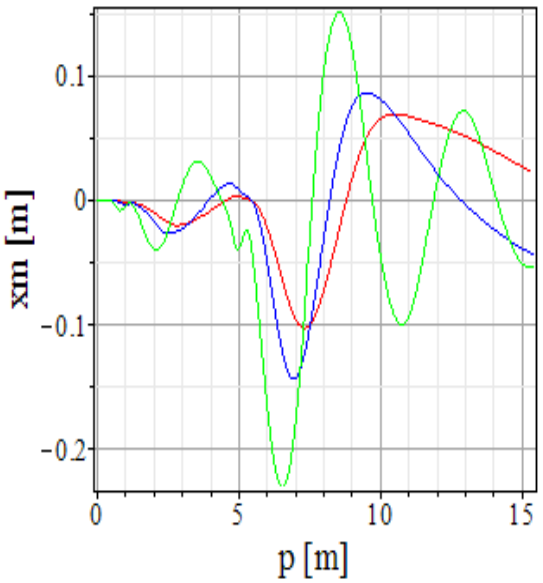


Fig. 10. Displacement of the superstructure (red: 50 km/h, blue: 30 km/h, green: 10 km/h)

It can be seen in Fig. 10 that the displacement is increased in case of the speed of the vehicle is increased. The peak displacement is 0.22 m when the speed is 10 km/h and is 0.1 m in case of 50 km/h. The setting time is lower when the velocity is lower.

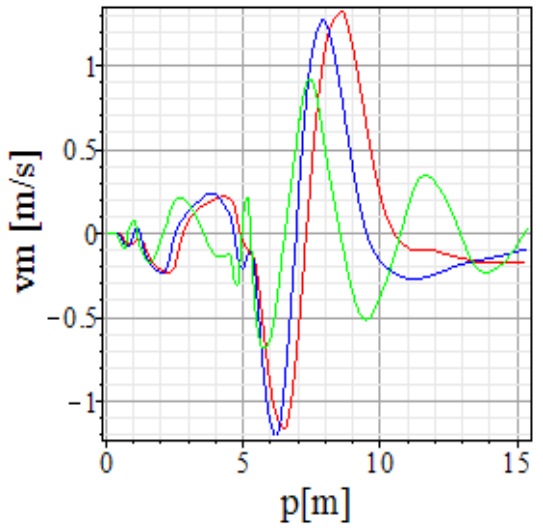


Fig 11. Velocity of the superstructure (red: 50 km/h, blue: 30 km/h, green: 10 km/h)

The velocity is increased as the speed of the vehicle is increased (Fig 11). The velocity is lower in case of 10 km/h, but there is no significant difference between 30 km/h and 50 km/h.

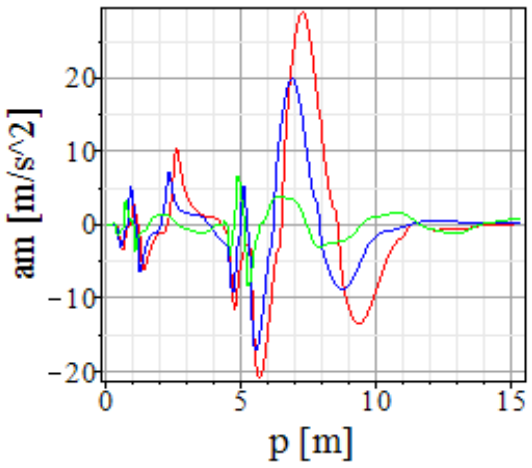


Fig 12. Acceleration of the superstructure (red: 50 km/h, blue: 30 km/h, green: 10 km/h)

The acceleration is increased when the speed of the vehicle is increased (Fig 12). The peak value is 29 m/s^2 in this case, which is almost 3 g acceleration. It might cause damage to the equipment. The peak acceleration value occur, when the rear wheel hits the pothole in all cases.

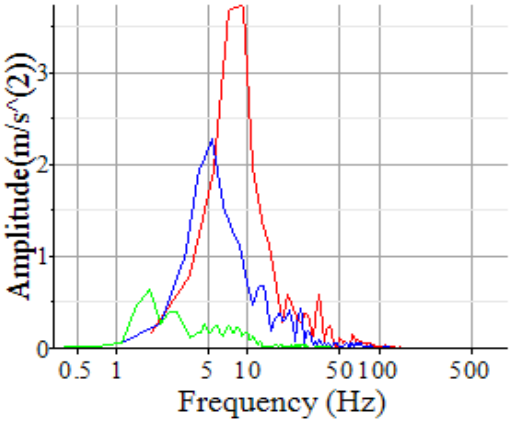


Fig 13. Frequency of the superstructure (red: 50 km/h, blue: 30 km/h, green: 10 km/h)

In Fig 13 it can be seen that the main frequency is 2 Hz in case of 10 km/h, 5 Hz in case of 30 km/h and 8 Hz in case of 50 km/h. These frequencies can be harmful for the human [[19]]-[[20]]. There are other smaller frequency components in all cases. The harmful effect for the vehicle and the equipment of these frequencies will be the task of further research.

The RMS (root mean square) values of the superstructure can be seen in Table 2.

Table 2. RMS values of the superstructure

	Displace-ment [m]	Velocity [m/s]	Acceleration [m/s^2]
10 km/h	0.082	0.32	1.93
30 km/h	0.052	0.47	6.07
50 km/h	0.046	0.51	9.12

It can be seen that the RMS of the displacement is lower than 0.1 m in all cases. In case of the velocity

the RMS value is lower in case of 10 km/h, and is increasing as the velocity of the vehicle is increased. Between 30 km/h and 50 km/h the difference is only 0,04 m/s. The RMS of the acceleration is increased as the velocity of the vehicle increased. In case of 50 km/h the RMS in 9.12, which is almost a g acceleration, which can cause damage.
The RMS values of the displacement and the acceleration of the front and rear axle can be seen in Table 3.

Table 3. RMS values of the front and rear axle

	x_f [m]	x_r [m]	a_f [m/s^2]	a_r [m/s^2]
10 km/h	0.047	0.056	5.05	5.65
30 km/h	0.041	0.061	18.47	18.87
50 km/h	0.04	0.059	28.02	27.6

It can be seen that the RMS of the displacement is larger on the rear axle. The RMS value is the largest in case of 30 km/h. The RMS of the acceleration are similar both on the front and rear axle. In case of 50 km/m the RMS value is larger on the front axle. The RMS value is almost 3 g in case of 50 km/h, which might even lead to break. Examination of the possible damage caused by road failures will be further research task.

CONCLUSIONS

In this study the harmful vibrations caused by a single pothole was examined in case of a special fire truck. Urban conditions were examined with 3 different vehicle speeds. Measured pothole profile was implemented to simulation environment as a Spline function. It was observed that in case of the velocity of the vehicle was increased the displacement of the superstructure was decreased, but the velocity and the acceleration was increased. In case of 50 km/h the peak acceleration of the superstructure was almost 3 g and the RMS was almost 1 g. The RMS was almost 3 g in case of the axles, which is harmful. It can be concluded that a pothole is primary harmful for the axles, but its effect cannot be neglected also on the superstructure, therefore at the carried equipment too. As the speed of the vehicle was increased the frequency was also increased with greater amplitude too. Next research task is to examine the effects of other road failures as well and extreme operation conditions (e.g. acceleration-braking, steady position during fire-fighting). The harmful effect of more road failures on a road will also be examined. A more accurate tire model with more contact points to the road will also be used in the future. The damage caused by road failures (break, fatigue) will be studied further with Finite Element Analysis. With our research we want to discover the effects of harmful vibrations in case of special fire trucks, determine their security risks and develop methods to avoid them for more effective and safe firefighting.

EMBERI ERŐFORRÁSOK MINISZTÉRIUMA

ACKNOWLEDGMENTS

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

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