BLAST WAVE AND SUSPENSION SYSTEM INTERACTION- NUMERICAL APPROACH

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Abstract

The main aim of this paper is to present the effective example of coupled experimental and numerical tests. Moreover, a development process of a numerical model of a terrain vehicle suspension system is presented. Experimental tests were carried out on the machine Instron 8802 with an assistance of the high-speed camera Phantom v12. Obtained stress-strain curves were applied into the FE model to estimate material constants for Mooney-Rivlin constitutive rubber model and for numerical failure criterion. Geometry of the tire and other suspension elements were achieved using reverse engineering technology. Due to the fact that a tire is such a complex structure to be represented with numerical methods, it was important to develop a discrete model of tire as much similar to the real one as possible. Consequently, an exact tire cords pattern was implemented into the FE model of the tire, which was obtained by the assistance of a microscope and X-ray device. In the next step, numerical analyses were performed simulating the TNT explosion under the suspension system with a simplified motor-car body. Non-linear dynamic simulations were carried out using the explicit LS-Dyna code, with central difference scheme with modified the time integration of the equation of motion. In order to simulate the blast wave propagation the Smoothed Particle Hydrodynamics (SPH) method and Arbitrary Lagrangian-Eulerian formulation with Jones Wilkins Lee (JWL) equation defining the explosive material were used. Finally, results from both approaches were compared.

Keywords: *suspension system, pressure wave, SPH, ALE, FE modelling*

1. Introduction

Due to its mechanical characteristics, including ability to reversible deformation under the loading of mechanical forces, rubber is very popular in various forms in many industries. One of these branches is the automotive industry, where materials and rubber-based composites are often used to produce tires with high strength and durability.

Behaviour of a vehicle while driving depends mostly on the characteristics of the wheel and other factors affecting the behaviour of the tire, e.g. soil, sand, mud or snow. In the vehicles for military purpose, a very important aspect is the disruptive strength of the wheels, which are shot by rifles or subjected to pressure wave of explosive materials. Their destructive effect manifests in a tire tearing apart followed by a large deformation of other suspension system elements. Moreover, reflected blast wave interacts with suspension elements dealing more overall damage to vehicle chassis. Therefore, it is significant to strengthen as much as possible the structure of a tire.

The authors of the presented paper came to conclusion that there is a need to perform numerical computations of a pressure wave interaction with suspension system of terrain vehicle and blast wave reflection effect taking into account. From the obtained results it will be possible to estimate the destruction mechanism of a blast detonation process [1,2], and in the further work, to improve its strength and durability.

Explosion process is an exothermic reaction, which is produced from external effects. As a result of this mechanical reaction highly compressed hot gases are formed. Consequently, a pressure surge is generated in the surrounding medium reaching values of tens GPa. The velocity of generated detonation wave can increase from 1000 m/s to 10000 m/s [3].

Such complex phenomenon as a detonation process of TNT high explosive material was simulated in the performed numerical computations based on two different approaches, e.g. Smoothed Particle Hydrodynamics (SPH) method and ALE (Arbitrary Lagrangian-Eulerian) formulation.

2. Experimental tests

One of the main parts of a suspension system is a tire. Due to the fact that it is such a complex structure to be represented with numerical methods, it was important to develop a discrete model of tire as much similar to the real one as possible. There was a need to perform experimental compression and tension tests of the tire rubber, from which stress-strain curves would be obtained. In order to carry out such investigations rubber coupons were cut out from the off-road vehicle tire. Experimental tests were carried out on the machine called Instron 8802 with an assistance of the high-speed camera Phantom v12 (Fig. 1).

Fig. 1. High-speed camera Phantom V12 and strength machine Instron 8802

Firstly, it was necessary to cut out slices of rubber with total thickness of 3-4 mm, from which tension coupons were obtained. Due to the complexity of the tire tread structure from this area it was possible to make only cylindrical coupons for the compression tests, whereas from the sidewall only coupons for the tension tests. The cords pattern was verified with microscope and X-ray device, which was necessary to cut out the rubber coupons without cords. Otherwise, obtained results from the experimental tests would give unreliable results.

With a software Tema 3.3 it was possible to perform measurements of a deformation in tensile tests by tracking displacements of the positioning points on a sample. Computed strain values were synchronous recorded with the force values from Instron machine. From the carried out tests mechanical characteristics of tire rubber (from tread and sidewall) were obtained. Fig. 2 presents the stress-strain curve with corresponding tension coupons, whereas curve with the compression coupons is presented in Fig. 3.

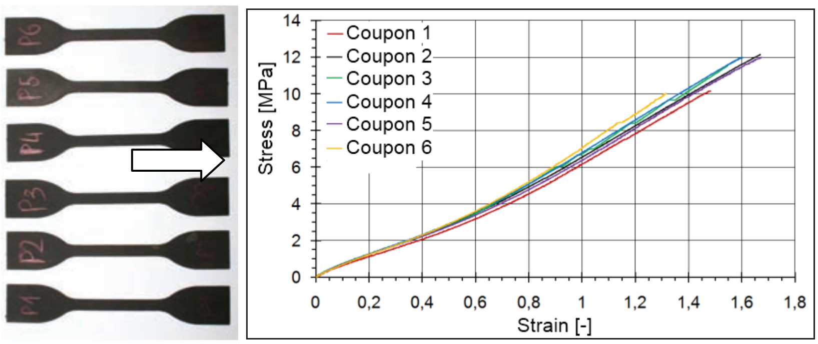

Fig. 2. Stress-strain curve obtained from tension experimental tests (tension coupons on the left)

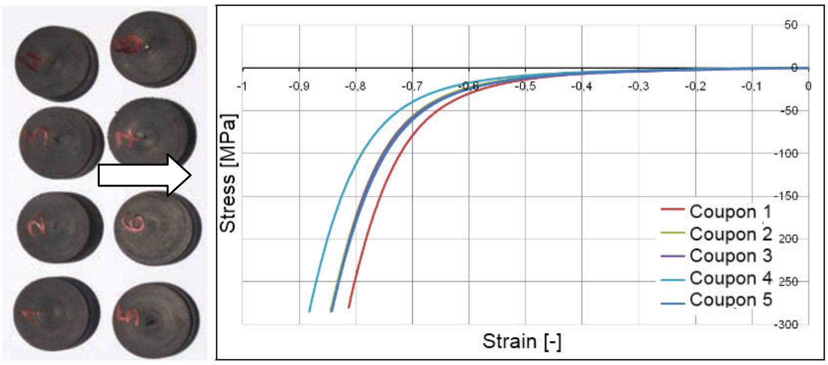

Fig. 3. Stress-strain curve obtained from compression experimental tests (compression coupons on the left)

3. FE modelling

As stated before an object of investigations of presented researches is the suspension system of the terrain vehicle. The major suspension system parts are: motor-car body, longitudinal, spring, axle, axle bush, hub, drum brake, drum brake pads, steel rim and wheel. Geometry of the tire and other suspension elements was achieved thanks to the reverse engineering technology. Experimentally obtained stress-strain curves were applied to estimate material constants for Mooney-Rivlin constitutive rubber model of the tire, which was divided into six different parts, with corresponding material properties (with experimental data added) and with steel cords arranged radially and circumferentially [4-6]. All of the above data concerning the modelling of the tire can be found in the previous authors' literature [7].

4. Simulated problem

Pressure wave interaction with suspension system was numerically represented with two different approaches, e.g. Smoothed Particle Hydrodynamics (SPH) method and ALE (Arbitrary Lagrangian-Eulerian) formulation [8]. In the performed studies the suspension system with a simplified motor-car body was taken into consideration, which was necessary to investigate the blast wave reflection effect. Due to the fact, that such simulations are computationally demanding only one wheel and 1/4 of the vehicle body was modelled with applied symmetry conditions. Pressure inside the tire was represented by the airbag model (Green function closed volume integration) [8]. In order to simulate the tire destruction the erosion criteria based on strain failure variable (taken from experimental tests) was implemented. Analyses were carried out with the 6 kg high explosive (HE) material situated at the distance of 0.3 m under the wheel displaced with 0.3 m toward the end of axle.

In both carried out simulations it was necessary to implement the detonation process of TNT high explosive material into the model using so called “explosive burn” material model. In this approach the energy of HE is assumed to be suddenly released inside the front of detonation wave. Detonation process requires to model the movement of the products of detonation (PD) after they reach subsequent specific locations by the detonation wave (DW) front. Applied explosive burn model was defined with the Jones-Wilkins-Lee (JWL) equation of state with the following form [3, 8]:

$$p = A\left(1-\frac{\omega}{R_1\bar{\rho}}\right)exp\left(-R_1\bar{\rho}\right)+B\left(1-\frac{\omega}{R_2\bar{\rho}}\right)exp\left(-R_2\bar{\rho}\right)+\frac{\omega\bar{e}}{\bar{\rho}}, \qquad (1)$$

where:

$\rho = \frac{\rho_{he}}{\rho}$ - density of products of detonation,

$e = \rho_{he}e$ - specific internal energy of PD,

ρ_{he} - refers to density of HE,
p - represents pressure of PD,
A, B, R_1, R_2, ω - empirical constants determined for the specific type of HE.

Values of the mentioned used for the computations are presented in Tab. 1.

Tab. 1. TNT constants for the JWL equation of state [9]

Material	P [kg/m^3]	A [Pa]	B [Pa]	R1 [-]	R2 [-]	ω [-]
TNT	1630	3.712e+11	3.231e+9	4.150	0.950	0.3

Smoothed Particle Hydrodynamic blast modelling

In this case the explosive charge was modelled with 300000 SPH particles, which was necessary to reflect a hydrodynamic behaviour of the blast wave propagation. In order to reduce the computation time, a box envelope was specified, within which SPH particles approximations are computed. This eliminates particles that are no longer interacting with the suspension system. Modelled suspension system with SPH explosive charge is presented in Fig. 4.

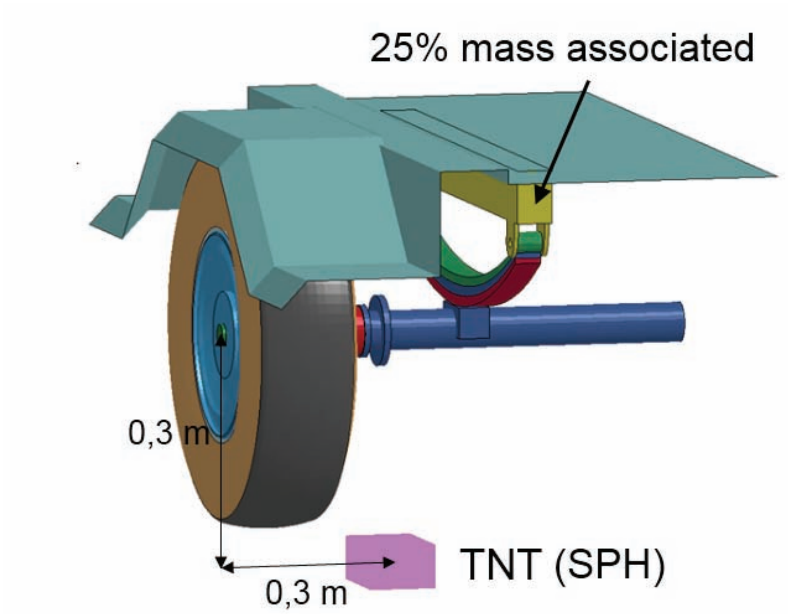

Fig. 4. Suspension system with SPH blast modelling

Smoothed Particles Hydrodynamics is a meshless particle method with Lagrangian nature, where computational information including mass and velocity are carried with particles. The main difference between classical methods and SPH is the absence of a grid. Therefore, those particles are the frameworks on the region within the governing equations are solved [8]. SPH method uses the concept of kernel and particle approximation as follows [8]:

$$\Pi^k f(x) = \int f(y) W(x-y, h) dy, \tag{2}$$

where W is the kernel function, which is defined using the function (θ) by the relation:

$$W(x,h) = \frac{1}{h(x)^d} \theta(x), \tag{3}$$

where d is the number of space dimensions and h is the so-called smoothing length which varies in time and in space.

Arbitrary Lagrangian-Eulerian blast modelling

In the ALE approach HE was situated identical as in the SPH modelling (Fig. 5). Also, its burn properties were defined by the JWL equation of state. In this case it was necessary to define an Eulerian air domain, in which the explosive pressure wave will propagate. Additionally, on the outer walls of it a non-reflecting option was applied, which considers the flow of the pressure outside the domain. The air is considered as simple ideal gas with linear polynomial equation of state [8]:

$$p = \left(C_4 + C_5 \mu\right) E, \tag{4}$$

where:

$\mu = \dfrac{\rho}{\rho_0}$,

ρ - density,
ρ_0 - initial density,
C_4, C_5 - polynomial equation coefficients,
E - internal energy.

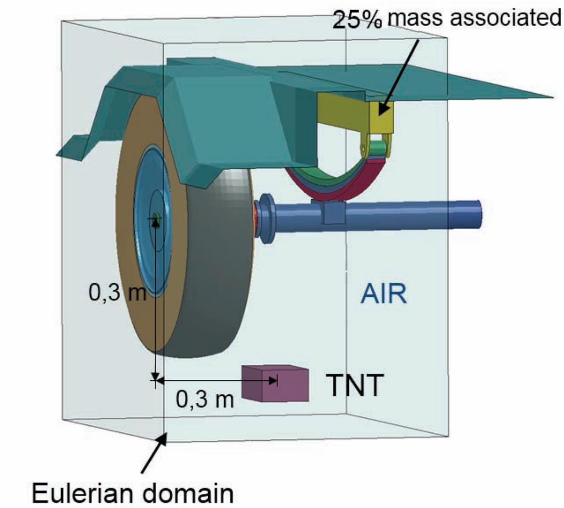

Fig. 5. Suspension system with ALE blast modelling

The ALE procedure consists of two major steps: the classical Lagrangian step and the advection Eulerian step. The advection step is carried out with the assumption that nodes displacements are very small in comparison with characteristics of elements surrounding these nodes, e.g. dimensions. Moreover, in this procedure a constant topology of mesh grid is prioivided.
The governing equations for the fluid domain (Euler domain) describe the conservation of mass, momentum and energy:

$$\frac{dM}{dt} = \frac{d}{dt}\int_{V(t)} \rho dV = \oiint_{S(t)} \rho(\underset{\sim}{w} - \underset{\sim}{v}) \cdot \underset{\sim}{n} dS \quad , \tag{5}$$

$$\frac{d\underset{\sim}{Q}}{dt} = \frac{d}{dt}\int_{V(t)} \rho \underset{\sim}{v} dV = \oiint_{S(t)} \rho \underset{\sim}{v}(\underset{\sim}{w} - \underset{\sim}{v}) \cdot \underset{\sim}{n} dS - \int_{V(t)} \underset{\sim}{\nabla} p dV + \int_{V(t)} \upsilon \underset{\sim}{g} dV \quad , \tag{6}$$

$$\frac{dE}{dt} = \frac{d}{dt}\int_{V(t)} \rho e dV = \oiint_{S(t)} \rho e(\underset{\sim}{w} - \underset{\sim}{v}) \cdot \underset{\sim}{n} dS - \int_{S(t)} p \underset{\sim}{v} \cdot \underset{\sim}{n} dS + \int_{V(t)} \rho \underset{\sim}{g} \cdot \underset{\sim}{v} dV \quad , \tag{7}$$

where:

ρ - fluid mass density,
p - pressure,
$\underset{\sim}{g}$ - acceleration of gravity,
e - total specific energy.

The quantities M, Q and E are total mass, total momentum and total energy, respectively, of a control volume $V(t)$, bounded by a surface S, which moves in the fluid (gas-air) with arbitrary velocity $\underset{\sim}{w}$ which may be zero in Eulearian coordinates or $\underset{\sim}{v}$ in Lagrangian coordinates. The vector $\underset{\sim}{n}$ is the outwards normal to the surface S.

5. Numerical simulations and results

To solve both presented cases the explicit central difference scheme with modified time integration of the equation of motion was implemented. In this method an velocity and acceleration are given by [9]:

$$\dot{x}_{n+\frac{1}{2}} = \frac{1}{\Delta t_{n+\frac{1}{2}}}\left[x_{n+1} - x_n\right], \tag{8}$$

$$\ddot{x}_n = \frac{1}{\Delta t_n}\left[\dot{x}_{n+\frac{1}{2}} - \dot{x}_{n-\frac{1}{2}}\right]. \tag{9}$$

The semi-discrete matrix equation of motion for the nonlinear case is then [9]:

$$\mathrm{M}\ddot{x}_n = \mathrm{F}_n^{ext} - \mathrm{F}_n^{\mathrm{int}} - \mathrm{C}\dot{x}_n, \tag{10}$$

where:

M - is global mass matrix,

C - global damping matrix,

F_n^{ext} - exterior forces vector,

$\mathrm{F}_n^{\mathrm{int}}$ - interior forces vector.

To achieve stability of computations it is necessary to meet the Courant-Friedrichs-Lewy (CFL) condition, which states that a necessary condition for the convergence of an explicit finite difference scheme is that the domain of dependence of the discrete problem includes the domain of dependence of the differential equation in the limit as the length of the finite difference steps goes to zero.

From the carried out analyses the tire destruction and overall model deformation was obtained. In Fig. 6 simulation results for the two chosen moments of time (t_1=0.005 s and t_2=0.025 s) are presented.

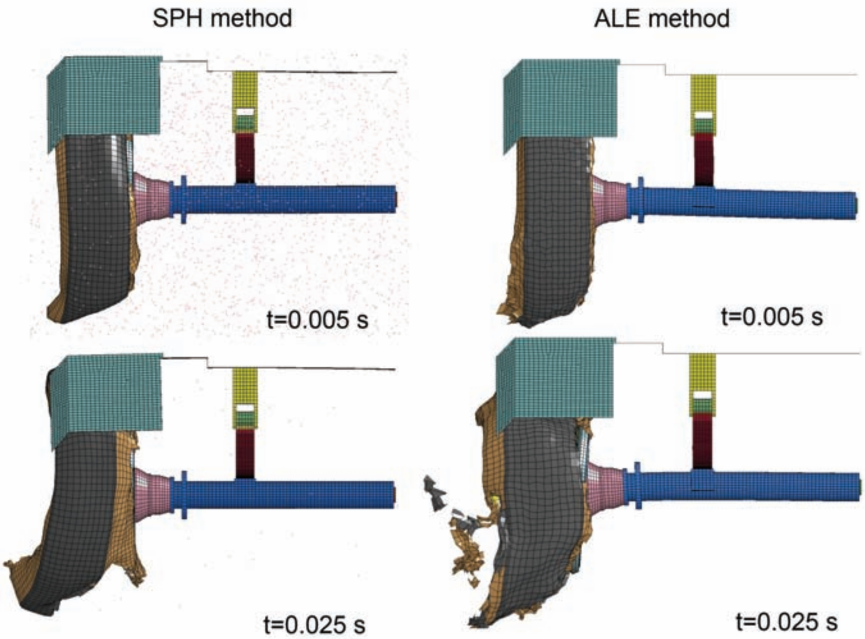

Fig. 6. Results comparison for both methods (left: SPH method, right: ALE method)

It can be noticed, that for the same moment of time the tire destruction isn't identical for both methods. In the ALE formulation approach pressure wave caused more damage to vehicle chassis elements, especially to the wheel. Thus this means that more internal energy is absorbed by the tire, what can be noticed in Fig. 7, which shows the tire internal energy versus time curve. In Fig. 8 tire destruction at t_2=0.025 s is presented for both cases.

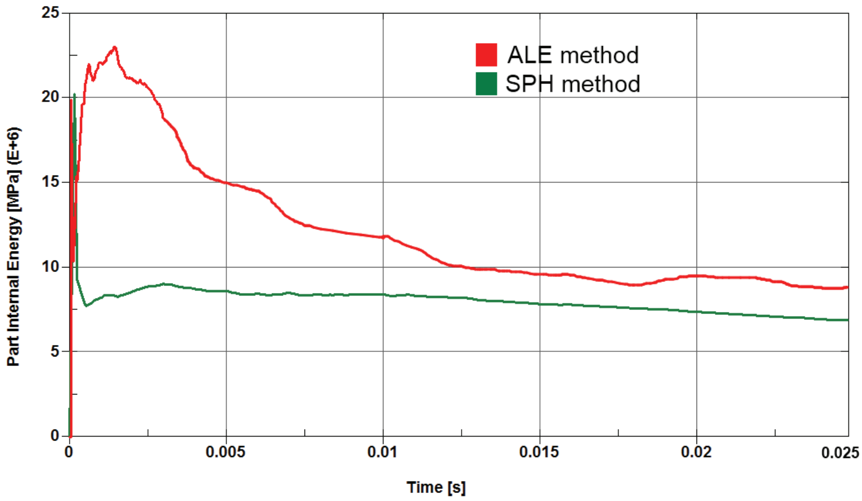

Fig. 7. Tire internal energy graph for both methods

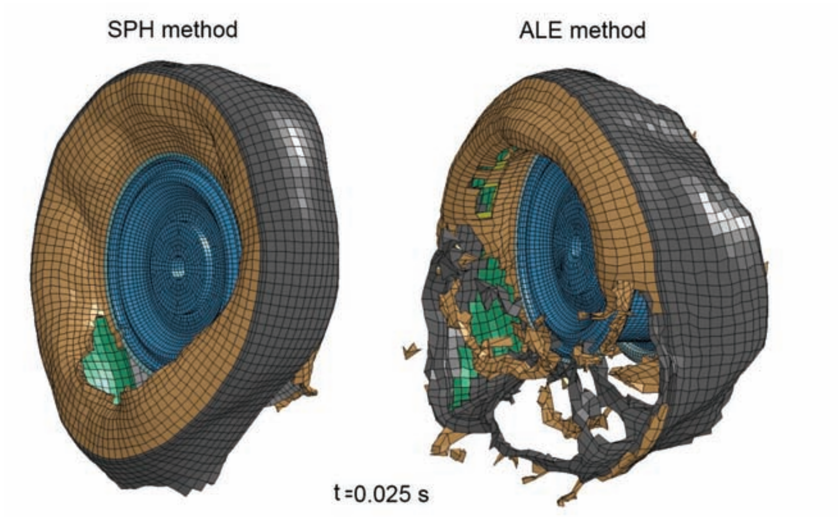

Fig. 8. Tire destruction for both cases at t_2=0.025 s

6. Conclusions

In this paper the authors have performed simulations of the vehicle suspension system with motor-car body subjected to the blast wave modelled with SPH method and ALE formulation. Carried out analyses have completely confirmed destructive effect of the explosion under the vehicle wheel. From the obtained results in can be noticed that the most devastated element of the examined suspension system is the tire, which consumes most of the explosive energy.

In the ALE method it can be noticed, that the pressure wave causes more damage to the vehicle chassis, especially to wheel and tire. Moreover, reflected blast wave results not only in destruction of the tire bottom but also of the upper side of it. In the further work proposed blast modelling will be thoroughly investigated in order to find the most efficient and effective method for simulating a dynamic loading such as explosion. Additionally, the influence of the soil will be tested, which will be simultaneously verified in field tests.

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