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TIRE PERFORMANCE AFTER EXPLOSIVE DECOMPRESSION

Grzegorz MOTRYCZ*, Piotr STRYJEK*, Jerzy EJSMONT, Henryk KAŁWA*****

* *Military Institute of Armored and Automotive Technology Sulejówek, Poland*
e-mail: grzegorz.motrycz@witpis.eu
e-mail: p.stryjek@wp.pl
** *Machinery Group at the Mechanical Faculty of the Technical University of Gdańsk, Poland*
e-mail: wiesiek@mech.pk.edu.pl
*** *Proxy Office of the Minister of National Defense for Wheeled Armored Fighting Vehicle, Poland*
e-mail: kalwah@tlen.pl

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This article presents the results of experimental investigations of an explosive decompression of an Armoured Personnel Carrier's tire. Despite a large number of empirical studies related to tire blow-outs aimed at improving the safety of personnel doing repairs and maintenance of trucks, the experimental data concerning tire explosions during driving are very limited. The main reasons are: the lack of objective test criteria and practical problems with the execution of tests.

It should be mentioned that, in the case of civilian vehicles, vehicle stability tests are performed during an explosion of the steering axle's tire. Such tests are mandatory for long-distance coaches that are certified to drive with the speed of 100 kph.

Unfortunately, during the obligatory stability tests of civilian vehicles the data are not recorded and no database with results is created. As a result, such tests do not lead to a better understanding of the phenomena occurring during a tire explosion.

The problem of vehicle performance during and after a tire explosion is critical for military vehicles, especially vehicles operating in high IED risk areas, like Afghanistan.

Keywords: *tire, armoured personnel carriers, run-flat reinforcement*

1. DESCRIPTION OF THE PHENOMENON

The basic concepts of the wheel dynamics that are presented in this paper are derived from the driven wheel that is in non-steady state conditions, which is the most general case. The diagram of forces and moments influencing such wheels is shown in Fig.1. The resultant force between tire and road surface acting in point 0_1 may be decomposed to two components: P, Z_k.

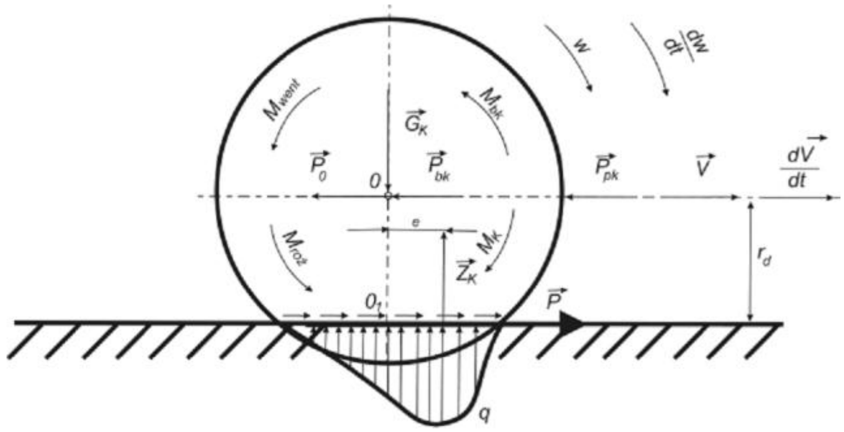

Fig. 1. Forces and moments influencing the driven wheel of a vehicle driving on rigid road surface

Source: Own elaboration

Here it is anticipated that the location of point 0_1 is known. The case is therefore analyzed in a formal manner.

It is known that the forces and moments acting on the wheel (including inertial forces and moments) must be balanced. Therefore, the following three equations may be formulated:

$$\vec{P}_0 + \vec{P}_{bk} + \vec{P}_{pk} + \vec{P} = 0 \tag{1}$$

$$\vec{G}_k + \vec{Z}_k = 0 \tag{2}$$

$$\vec{e} \times \vec{Z}_k + \vec{r}_d \times \vec{P} + \vec{M}_k + \vec{M}_{łoż} + \vec{M}_{went} + \vec{M}_{bk} = \vec{0} \tag{3}$$

After having considered the directions of forces and moments, the presented vector equations may be presented as the following algebraic equations:

$$P = P_0 + P_{bk} + P_{pk} \tag{4}$$

$$G_k = Z_k \tag{5}$$

$$M_k = e \cdot Z_k + r_d \cdot P + M_{łoż} + M_{went} + M_{bk} \tag{6}$$

and:

$$P_{bk} = m_k \cdot \frac{dV}{dt} \tag{7}$$

$$M_{bk} = I_k \cdot \frac{d\omega}{dt} = \frac{I_k}{r_t} \cdot \frac{dV}{dt} \tag{8}$$

where:

m_k – mass of the wheel;

I_k – inertia momentum of the wheel in relation to its axis of rotation;

From (5) and (6) we calculate M_k

$$M_k = e \cdot G_k + r_d \cdot P + M_{łoż} + M_{went} + M_{bk} \tag{9}$$

product of eG_k we call the rolling resistance torque, i.e.:

$$M_t = e \cdot G_k = e \cdot Z_k \tag{10}$$

The rolling resistance torque M_t expressed by formula (10) is an abstract notion. After dividing (9) by r_d we obtain:

$$\frac{M_k}{r_d} = \frac{e}{r_d} \cdot G_k + P + \frac{M_{łoż}}{r_d} + \frac{M_{wew}}{r_d} + \frac{M_{bk}}{r_d} \tag{11}$$

The ratio of driving torque M_k and dynamic tire radius r_d is defined as driving force p_n.

Therefore:

$$P_n = \frac{M_k}{r_d} \tag{12}$$

Equation (12) is especially important in providing the basis for the vehicle's stability. The driving force provided by the driven wheel depends on the driving torque supplied by the power train and tire radius. It is anticipated that the driving torque is evenly distributed between all driven wheels.

2. FIELD TESTS

2.1. Tested object

A four-axle, armored combat vehicle *KTO Rosomak* presented in Fig. 2 was used during the investigations. The vehicle is 8 m long and its total mass during the tests was 18425 kg. The vehicle was equipped with multi-purpose tires of the size 14.00R20. The wheel base between the 1st and the 2nd axle was 1.405 m, between the 2nd and the 3rd axle - 1.705 m, and between the 3rd and the 4th axle - 1.452 m. The weight distribution on the particular axis was: on the 1st axle - 5715 kG, on the 2nd axle - 5015 kG, on the 3rd axle - 4275 kg, on the 4th axle - 3420 kG [6]. The center of gravity was at a height of 1.24 m over the road surface at standard setting of the vehicle suspension, and 1.945 m rearward in relation to the 1st axle. The wheelbase of the vehicle is 2.45 m. The inertia moments of the vehicles hull (coordinate system linked to the vehicle, 1) were: I_x= 21220 kg/m^2, I_y=90720 kg/m^2, I_z= 98000 kg/m^2. Moments of inertia have been determined by calculations.

Fig. 2. Wheeled Armoured Vehicle (Rosomak) - basic version

Source: Own elaboration

The aim of the testing was to establish the properties of a wheel equipped with a tire designed for operation under a wide range of inflation pressure and equipped with the Run Flat reinforcement (Fig. 3).

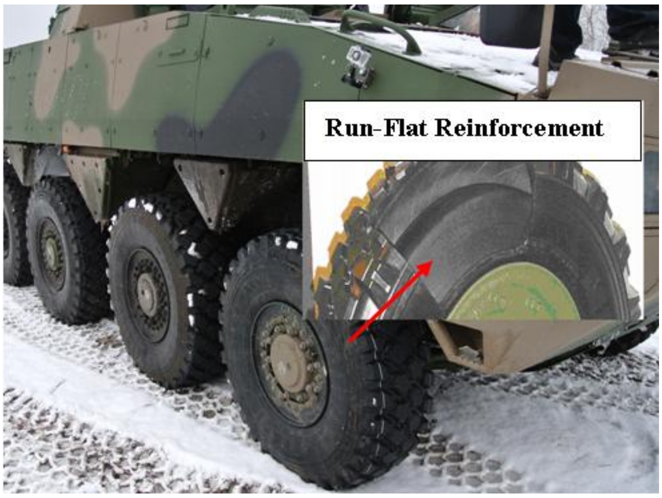

Fig. 3. View of the Nokian tire with a Run Flat reinforcement

Source: Own elaboration

There are two mechanisms of tire explosion. The first one is caused by mechanical damage of the tire sidewall. The other mechanism is related to the very strong mechanical impact acting on the tire.

The first mechanism usually has a few phases. First of all, mechanical damage to the tire sidewall leads to the separation of the carcass fabric from the rubber of the sidewall. After the separation extensive friction between interfacing layers leads to a heat build-up as well as carcass and rubber degradation. The threads of the carcass fabrics also become destroyed due to fatigue bending. After some time the tire may blow out, causing the loss of the vehicle's stability.

2.2. Preliminary (stationary) field tests

During the field tests the test team triggered damage to the tire mounted to a specially built fixture by detonating a shaped explosive charge "Blast" (see Fig. 4).

Fig. 4. Tyre decompression filmed 0,2 s after the detonation of the Blade charge

Source: Own elaboration

The test tire used during all experiments was: NOKIAN with a „run-flat" reinforcement, size - 14.00R20 160 G MPT AGILE TL (See Fig. 3).

The preliminary testing was aimed at the preparation of methodology and fine tuning of the explosive charges used to simulate explosive decompression.

2.3. Field testing

The following parameters were measured and registered during all tests: longitudinal (V_L) and transverse (V_Q) components of linear velocity vector, three components of angular velocity vector, three components of angular position of the vehicles hull.

Furthermore, three vector components of the vehicle linear acceleration, steering angle (δ_H) and torque on the steering wheel ($M_{\delta H}$) were measured and recorded.

During normal operation of the vehicle the tyre blow-out occurs due to an increase of temperature within the tire that results in increased inflation pressure and concurrent damage due to torque that weakens the tire's layers. The pressure increase continues up to the moment of blow-out of the tire or when the tire is ripped away from the rim. Additionally, starting with a certain temperature, chemical reactions begin to occur in the material of the tire, including chemical oxidation and pyrolisis (destructive distillation - irreversible chemical decomposition caused by high temperature). Due to the pyrolisis of the carcass material of the tire many flammable gases, like methane, styrene, butadiene or hydrogen, are released.

Figure 5 presents the distribution of temperatures of a rotating wheel (Nokian tire) with a „run-flat" reinforcement with no inflation pressure, at a speed of 80 kph. The temperature of certain regions of the tire sidewalls after 3 minutes of rolling increase to about 106^o C.

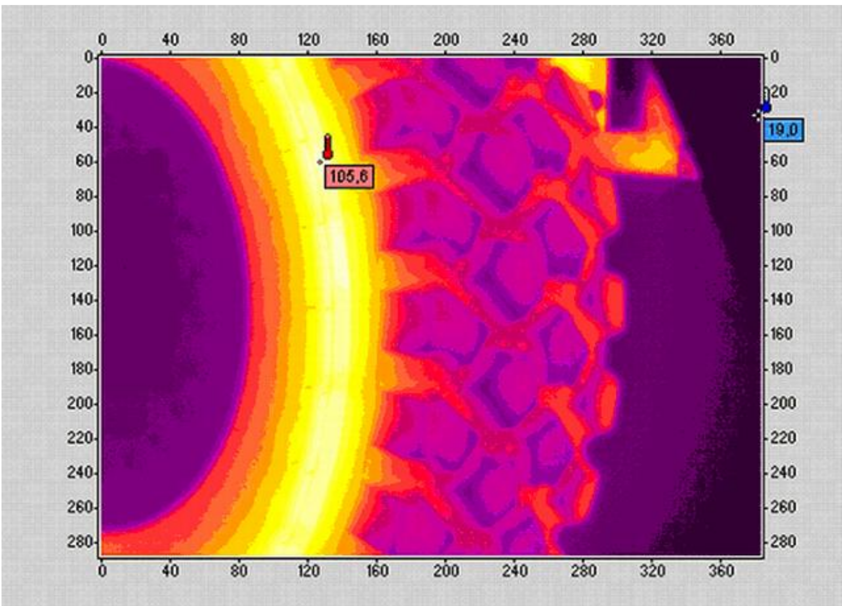

Fig. 5. The distribution of temperatures within the Nokian tire during rolling at a speed of 80 kph, with no inflation pressure

Source: Own elaboration

Figure 6 shows air and smoke blowing out of the damaged tyre. Due to the damage, the inflation pressure in the tire dropped to 0 kPa. According to the equation (12), the driving force available for each driven wheel is dependent on driving torque that may be assumed as constant and evenly distributed between all driven half-axles, and the dynamic radius of tire. Due to the explosion of a certain tire, its dynamic radius r_d changes rapidly.

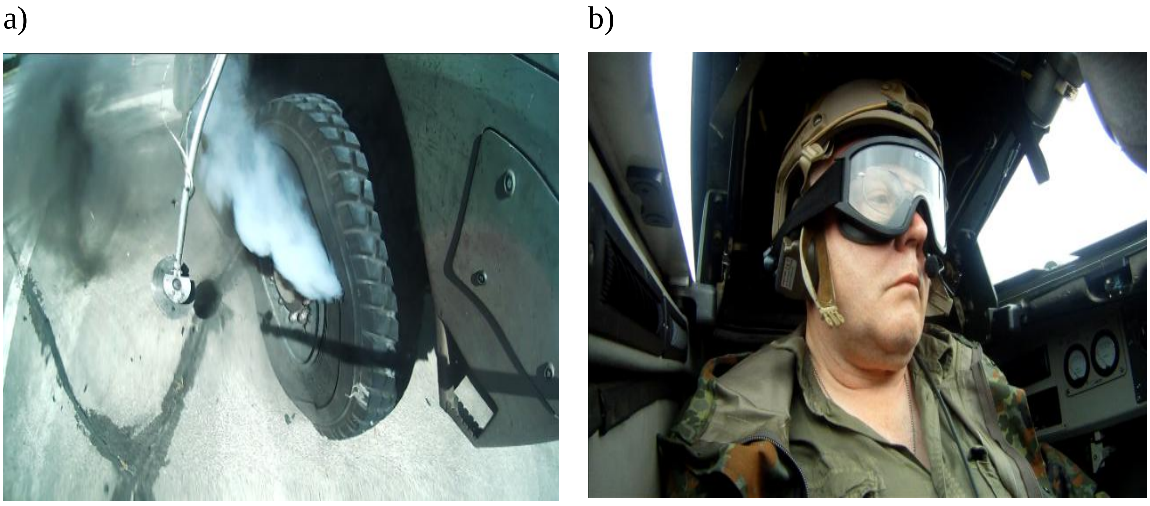

Fig. 6. a) - tire decompression after detonating the charge; b) – the driver's reaction to the sudden explosion.

Source: Own elaboration

3. RESULTS AND ANALYSIS

The oversteer/understeer gradient of the vehicle was chosen as the measure of steerability. The definition of this assessment indicator may be found in 3, 4. Establishing the under/oversteer gradient requires the characteristic of the change of steering gear angular displacement (δ_H) as function of transversal acceleration (a_y). The curve was determined indirectly by investigating the relation between the radius of the vehicle centre of gravity trajectory as a function of speed V_{sx} in form $R= f(V_{sx}^2)$ while driving in circles. The test was conducted by means of fixed position of the steering wheel (so called fixed control). This method is mostly used for testing large and heavy vehicles since the driver can focus on a regular (slow and steady) increase in vehicle speed which is essential in this test.

Having adopted a simplified 2D model of the vehicle, one may determine the relationship of the steering gear angular displacement as function of lateral acceleration. This simplified model can be described by the following equation 2:

$$(\delta_H - \delta_{HA}) = \delta_{H0}(1 - \frac{R_0}{R})[rad] \quad (13)$$

where:

δ_{HA} – steering gear angular displacement at transversal acceleration $a_y=0$ referred to as Ackermann angle,

δ_{H0} – constant steering gear angular position chosen at the beginning of the test,

R_0 – initial radius of the trajectory for acceleration $a_y \approx 0$.

The understeer gradient is defined as follows:

$$A_\delta = \frac{A_{\delta_H}}{i_s} \; [\mathrm{rad \cdot s^2 \cdot m^{-1}}] \tag{14}$$

where:

$A\delta_H$, $\mathrm{rad \cdot s^{2 \cdot} m\text{-}1}$, is a slope of the straight line which approximates the (δ_H-δ_{HA}), curve in the linear range of ($0<a_{y\leq}4\ \mathrm{m \cdot s^{-2}}$), i_s - steering system ratio.

Fig. 7 presents the relationships between (δ_H-δ_{HA}) and a_y, for the test of circular drive to the left in various conditions of the driving axle tires.

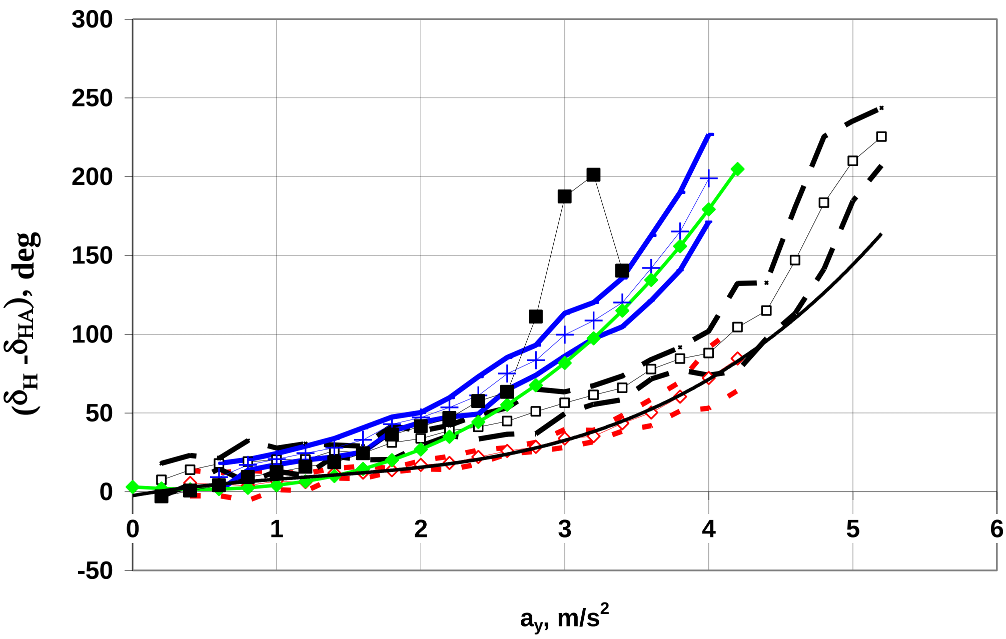

Fig. 7. Steering gear angular displacement changes as a function of lateral acceleration in a vehicle with the driving axle wheel tyres in various conditions; turning to the left.

Source: Own elaboration

The description of test conditions for Figure 7: rectangles no fill - vehicle in good standing; crosses - right tire of the first steering axle undamaged but not inflated; diamonds no fill - right tire of the first steering axle destroyed by explosion; diamonds filled - blown-out right wheel tyres of the first and second steering axles; rectangles filled - both tyres (left and right) on the first steering axle destroyed.

Table 1 shows the summary of numerical values of the vehicle slip angles at two opposite points located at the front and rear of the hull on the longitudinal symmetry plane of the vehicle. The table also includes conditions of the tires.

Based on the curves presented in Fig. 7, the vehicle understeer gradient was determined for each condition of the first axle right wheel tire. The summary of the values of this gradient is shown in table 2. Figure 8 presents the curve of the body transversal tilting angle φ as the function of time, and Figure 9 the angle as the function of lateral acceleration.

Table. 1. Vehicle SLIP angles at two opposite locations on the hull in various conditions of the first driving axle right wheel tire

Coordinates (x,y), of two locations in the vehicle coordinate system, projection on the roadway, [m]	Tire inflation pressure [kPa] ----------------- Drift angles for a_y=3 [m/s^2], Including standard deviations Degrees				
	[530 kPa] Rated	*[0 kPa] Undamaged tire*	*[0 kPa] Blown-out tire*	*[0 kPa] 2 blown-out tires, I and II axle right side*	*[0 kPa] 2 Blown-out tires on I axle*
(2.505; 0) 0.61m from axle I	4,45±0,21	6,29±0,32	4,21±0,25	9,42±0,85	9,57±0,93
(-3.025; 0) 0.42m from axle IV	2,01±0,15	0,66±0,09	0,96±0,28	1,05±0,35	0,76±0,27

Source: Own elaboration

Table. 2. Vehicle understeer gradient for different conditions of the front wheels

Condition of the tire on the first axle	vehicle understeer gradient[rad.s^2.m^{-1}]
Undamaged tire, inflation pressure = 53 kPa	0,011±0,002
Undamaged tire, tire noninflated	0,015±0,002
Blown-out tyre, tire noninflated	0,009±0,001

Source: Own elaboration

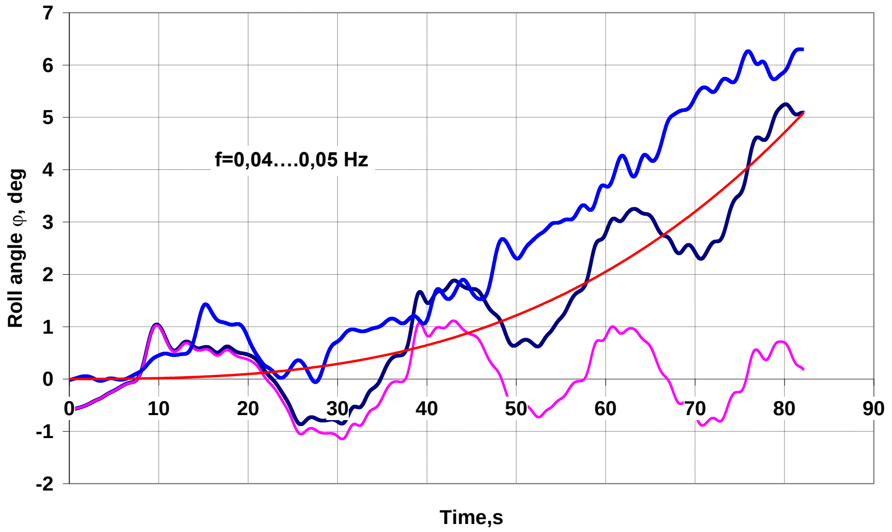

Fig. 8. The body transversal tilting angle φ, steady state circular drive to the left. The vehicle with an undamaged tire and at rated pressure = 530 [kPa] and with a blown-out tire. Considerable oscillations of the angle are visible in the case of the blown-out tire. The frequency of oscillations is about 0.9 [Hz].

Source: Own elaboration

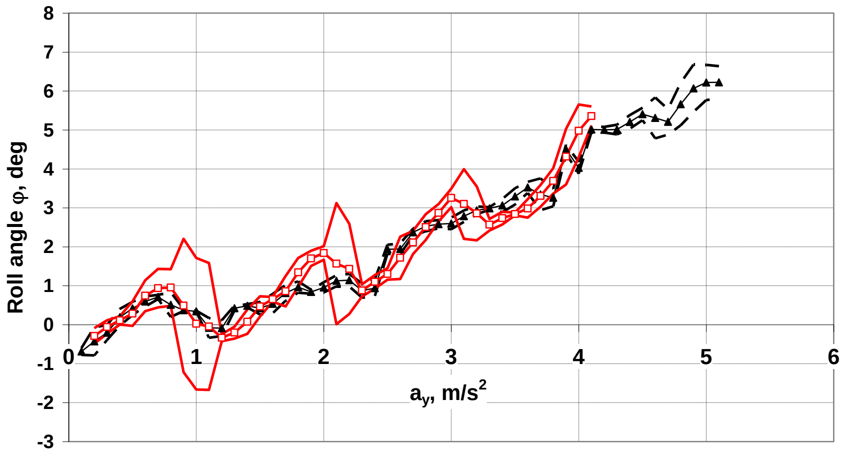

Fig. 9. Transversal tilting angle as the function of lateral acceleration. The average angle φ values in the case of blown-out tire are marked with rectangles.

Source: Own elaboration

CONCLUSIONS

Based on the test results, the following conclusions may be drawn:

1) The vehicle with an undamaged tire of steering axle I, with no inflation pressure, exhibits more understeer than at a nominal tyre pressure of 530 [kPa]. For a blown-out tire, the understeer of the vehicle, in relation to the above case, has decreased.
2) During the steady state circular drive test the vehicle with a blown-out tyre proved unstable, which manifested itself in distinct oscillations of the lateral tilting angle at a frequency of about 0.9 [Hz].

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ZACHOWANIE OPONY W CZASIE EKSPLOZJI DEKOMPRESYJNEJ

Streszczenie

Niniejszy artykuł przedstawia zjawisko eksplozyjnego rozerwania opon transporterów opancerzonych, przebieg i wyniki eksperymentu. Na świecie w wielu ośrodkach prowadzone były badania ukierunkowane na poprawienie ochrony ludzi, którzy zajmują się naprawą i konserwacją opon samochodów ciężarowych i zabezpieczeniem ich przed skutkami rozerwania opony. Niestety informacje o reakcji kierowców są raczej ograniczone, ponieważ nie istnieją żadne obiektywne kryteria oceny. Wiedza na temat zagrożeń i zachowania się pojazdów różnego typu podczas eksplozyjnych uszkodzeń ogumienia jest również niewystarczająca.

Należy zwrócić uwagę, że w przypadku pojazdów cywilnych prowadzone są próby stateczności pojazdu podczas eksplozji opony osi kierowanej. Tego typu badanie wykonuje się obligatoryjnie dla autobusów dalekobieżnych, dopuszczanych do ruchu z prędkością 100 km/h.

Podczas takich prób nie dokonuje się jednak pomiarów i rejestracji wyników, co pozwoliłoby na stworzenie choćby częściowej bazy danych, przydatnych np. w procedurach sądowych.

W przypadku pojazdów, których miejscem operowania są rejony ze wzmożonym ryzykiem występowania ładunków IED (np. Afganistan), przedstawiany problem jest aktualny.

Słowa kluczowe: *opona, wkładka run-flat, transportery opancerzone,*

BIOGRAPHICAL NOTE

Prof. Jerzy A. EJSMONT – has been an employer of the Gdansk University of Technology since 1978. Since then he has been involved in measurements of noise and rolling resistance forces caused by tires. He is an author of several scientific article and books related to tires. He is the head of a research group presently, with the use of a unique laboratory trailer for research and development works about tires field. He cooperates with many scientific institutes from all over the world, as well as being involved in research in military vehicles.

Henryk KAŁWA, PhD, Eng, – is currently an employer of the Ministry of National Defense. He has many years of experience in the field of military vehicle research. For many years he was involved in the processes of developing vehicles for the Polish Army. Over the last years he has been concerned with the evolution and implementation of the new version of the wheeled armored transporter "Rosomak".

Grzegorz MOTRYCZ, MSc, Eng, – graduated from the Military University of Technology. Over the last years he has been involved in the safety and steering ability of vehicles. He is an author of numerous articles and a co-author of a monograph concerning the steering ability of military vehicles. Last time he was the main executive of several research and development projects related to the dynamics of military vehicles.

Piotr STRYJEK, MSc, Eng, – graduated from the Warsaw University of Technology. He is currently employed at the Military Institute of Armour and Automotive Technology. Head of the Laboratory of Combat Armored Vehicles. Over the last years he has been involved in research and development projects and tests of military vehicles. An author or a co-author of several articles and a monograph concerning military and special purpose vehicles. He is a member of the National Standards Body in Poland: the Technical Committee of Tires and Vehicles.