# Selected issues of hydropneumatic suspension design for a high-speed tracked vehicle

# Wybrane zagadnienia projektowania zawieszenia hydropneumatycznego dla szybkobieżnego pojazdu gąsienicowego

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**Abstract.** The effective operation of high-speed tracked vehicles in a combat vehicle configuration depends primarily on the correct identification of the expected operating conditions, already in the design or modernisation phase. This applies to both terrain, meteorological and climatic conditions. This approach considers the most unfavourable driving conditions and the level of dynamic loads acting on the vehicle hull, crew and equipment when making calculations. The dominant source of dynamic loads is movement at high speed on unpaved roads, off-road and when overcoming natural and artificial terrain obstacles of a predetermined or random nature. An important system responsible for the safety and reliability of this type of vehicle is the suspension. An appropriate design of the suspension parameters allows to reduce

the negative dynamic loads (research hypothesis). The aim of the research was to develop a preliminary project of an initial suspension element – a hydropneumatic spring for a high-speed tracked vehicle - that allows minimising dynamic loads. The study used both theoretical and empirical research methods, including analysis, synthesis, deduction, induction, comparison and inference. The paper presents selected issues from the suspension design process for a high-speed tracked vehicle equipped with a hydropneumatic suspension. The problem was solved in three stages. In the first stage, the design of the hydropneumatic suspension unit, placed in the control arm, was made and the basic parameters were selected. In the second, the spring characteristic of the hydropneumatic unit was determined on the example of a hypothetical vehicle with assumed tactical and technical parameters. In the third stage, the strength of the control arm structure, under the heaviest load conditions, was checked using the Finite Element Method (FEM). The results obtained showed that the advantages of the hydropneumatic suspension, such as: progressive spring characteristics, improved vibration damping, possibility of introducing a semi-active or active suspension system, modularity of the structure and ease of maintenance and repair, make it more and more widely used in modern high-speed tracked vehicles.

**Keywords:** operation, high-speed tracked vehicle, hydropneumatic suspension, progressive spring characteristic, numeric analysis

**Abstrakt.** Efektywna eksploatacja szybkobieżnych pojazdów gąsienicowych, w konfiguracji wozu bojowego, związana jest głównie z właściwym, już na etapie projektowania lub modernizacji, określeniem przewidywanych warunków użytkowania. Dotyczy to zarówno warunków terenowych, meteorologicznych, jak też klimatycznych. Konsekwencją takiego podejścia jest przyjęcie najbardziej niekorzystnych warunków ruchu oraz poziomu obciążeń dynamicznych działających na kadłub pojazdu, załogę i wyposażenie. Dominującym źródłem obciążeń dynamicznych jest ruch ze znacznymi prędkościami po drogach nieutwardzonych, bezdrożach oraz podczas pokonywania naturalnych i sztucznych przeszkód terenowych o charakterze zdeterminowanym lub losowym. Istotnym układem odpowiedzialnym za bezpieczeństwo i niezawodność tego typu pojazdów jest zawieszenie. Odpowiedni dobór parametrów zawieszenia pozwala na ograniczenie negatywnych obciążeń dynamicznych (hipoteza badawcza). Celem badań było opracowanie projektu wstępnego elementu zawieszenia – resora hydropneumatycznego dla szybkobieżnego pojazdu gąsienicowego, pozwalającego na minimalizację obciążeń dynamicznych. W badaniu wykorzystano zarówno teoretyczne, jak i empiryczne metody badawcze, a wśród nich analizę, syntezę, dedukcję, indukcję, porównanie i wnioskowanie. W pracy przedstawiono wybrane zagadnienia z procesu projektowania zawieszenia dla szybkobieżnego pojazdu gąsienicowego wyposażonego w zawieszenie hydropneumatyczne. Zagadnienie rozwiązywano w trzech etapach. W pierwszym etapie wykonano projekt resora hydropneumatycznego zawieszenia typu wahaczowego i dobrano podstawowe parametry. W drugim wyznaczono charakterystykę sprężystości elementu hydropneumatycznego na przykładzie hipotetycznego pojazdu o założonych parametrach taktyczno-technicznych. W trzecim etapie, sprawdzono wytrzymałość konstrukcji wahacza przy najcięższych warunkach obciążenia z wykorzystaniem metody elementów skończonych. Otrzymane wyniki wykazały, że zalety zawieszenia hydropneumatycznego takie jak: progresywna charakterystyka sprężystości, poprawa tłumienia drgań, możliwość wprowadzeniu układu półaktywnego lub aktywnego zawieszenia, modułowość konstrukcji oraz podatność obsługowa i naprawcza sprawiają, że znajduje ono coraz szersze zastosowanie we współczesnych szybkobieżnych pojazdach gąsienicowych.

**Słowa kluczowe:** eksploatacja, szybkobieżny pojazd gąsienicowy, zawieszenie hydropneumatyczne, progresywna charakterystyka sprężystości, badania modelowe

# Introduction

Modern high speed tracked vehicles such as used tanks (e.g., M1 Abrams, Leopard 2PL, K2-Black Panther, Challenger 2, Leclerc, Altay, Anders and others) and infantry fighting vehicles (e.g., Puma, Bradley, Warrior, Borsuk and others) are characterized by a maximum speed on road conditions of up to 72 km/h with a curb mass of 28-72 t (Fig. 1). However, these are vehicles designed to operate on terrain with a varied profile of unevenness, which differs significantly from the profile of an asphalt or concrete road, even of inferior quality (Fig. 2). It should be noted that the type of ground, combined with the number of road wheels (on one side), affects the resistance of movement and the depth of the rut (Fig. 4). The general influence of the enemy and his means of combat on the dynamics of the vehicle's movement is also important. It should (if possible) complement the active protection. Therefore, for this type of vehicle, the so-called average off-road speed, and the time to reach a speed from 0 to 32 km/h (0 to 20 mph) are important. Experience shows that tank dynamics, i.e. acceleration measured by the time it takes to reach a speed from 0 to 32 km/h, is very important. High acceleration (short acceleration time) is needed to quickly change position, e.g. after illumination with a laser rangefinder to avoid being hit by modern anti-tank missiles. The ability to perform rapid maneuvers on the battlefield is an important tactical technique. The time to reach a speed from 0 to 32 km/h is a measurable parameter of active defense by changing the place of standing (position). The above-mentioned conditions, the need to ensure an appropriate level of ergonomics for the crew and the reliability of the internal equipment are the reasons for the high demands placed on the suspension of a high-speed tracked vehicle.

The suspension of a tracked vehicle is a set of mechanisms and parts that elastically (flexibly) connect the hull to the road wheels. The suspension has a significant impact on the smoothness of the vehicle's movement, the dynamics and effectiveness of combat operations, the durability and reliability of the vehicle. It is also an element that complements the active protection of vehicles and influences their ability to survive on the battlefield.

The main purpose of the work is the issue related to the development of a preliminary design of a suspension element – a hydropneumatic spring for a high-speed tracked vehicle. A spring with the desired, progressive spring characteristic and appropriate potential energy of the suspension, allowing to minimize the dynamic loads acting on the hull, crew, and internal equipment.

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Fig. 1. Main battle tanks during exercises at the Military Training Center of Land Forces - Żagań (Abrams M1A2 SEPV3 tank in the foreground)
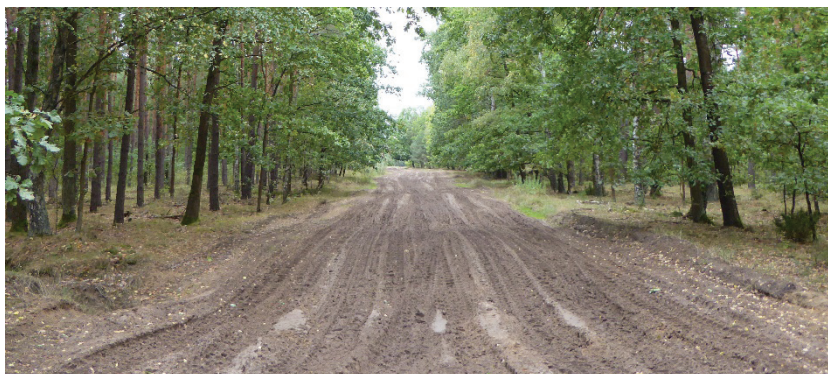Source: (Details of the Polish-American agreement EDCA – MILMAG 2023)



Fig. 2. Typical polygonal road
Source: Own study

## Analysis of the state of the issues in the literature

Issues related to the selection of spring and damping elements for high speed tracked vehicles are rarely found in the available publications. They are limited in scope, general in nature, or only partially cover the subject. In the article (Xu *et al.* 2017) the authors present the types of suspension components used, the advantages and disadvantages of individual solutions and the current directions of their development. The most commonly used spring elements in tracked vehicles are torsion bars or hydropneumatic components, prospective due to their progressive characteristic and the possibility of using the functions of flexible height and clearance

adjustment. Moreover, the general concept of the suspension system is changing from passive to semi-active and active, whereby changing the parameters of the suspension system, vehicle vibrations can be minimized. Semi-active suspension and research about it was described in more detail in the paper (Solomon, Padmanabhan, 2011). In the literature (Chodkowski, 1990) and (Burdziński, 1972) the authors describe, among other things, the method of preliminary computations in the selection of parameters and main dimensions of the suspension, as well as the rules for the selection of shock absorbers. These works specify the calculations of a classical suspension using a torsion bar as a spring element. The investigations of the hydropneumatic suspension (Fig. 3) are described in detail in the study (Bauer 2011) which contains methods for calculating and determining: elastic and damping characteristic, dimensions of hydraulic cylinders depending on the expected load range, suspension geometry, maximum possible pressure, static load, calculation of initial pressure and volume of gas accumulators, as well as the elements of the hydraulic shock absorber.



Fig. 3. Challenger tank hydropneumatic spring
Source: (External Suspension, Suspension for Armoured Vehicles 2022)
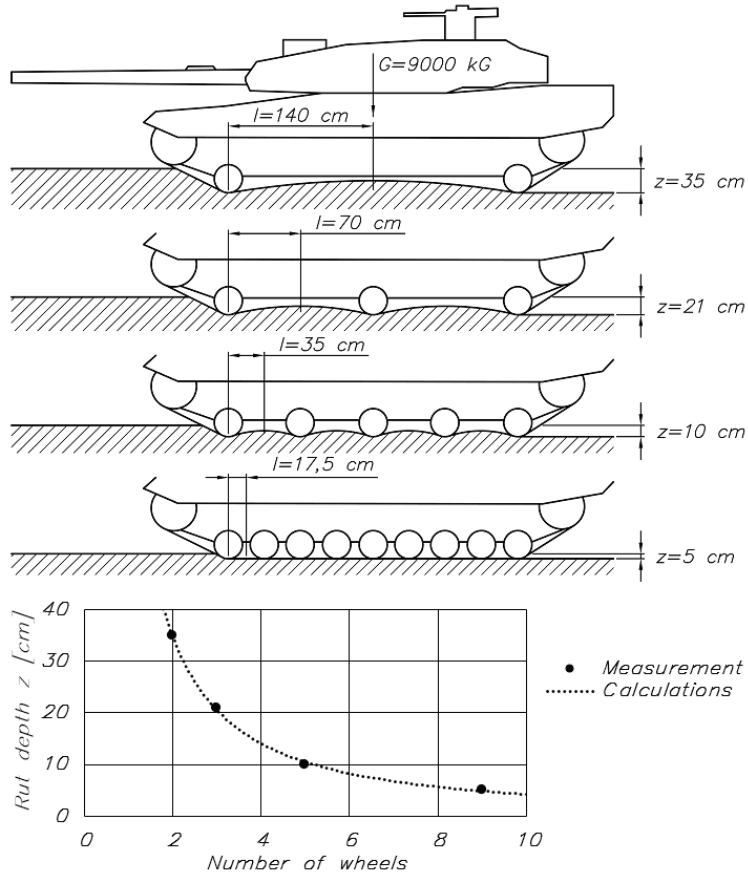
Fig. 4. The influence of the number of road wheels on the penetration of a tracked vehicle into muddy ground

Source: Own study based on (Bekker 1956), (Sołtyński 1966)

Currently, numerical modeling is used in the process of designing the suspension of a tracked combat vehicle, where the vehicle components tested in the simulations are analyzed as multi-unit systems, as in the studies: (Mura, 2013), (Qin *et al.* 2021) The authors of the publication (Balamurugan, Srinivasan 2017), (Razenberg, 2009) also use multivariate simulations of dynamic vehicle maneuvers to modify critical parameters and achieve better vehicle performance. The methodology presented in the previously mentioned article allows to reduce the time and cost of testing different versions of the vehicle in a dynamic environment before producing a physical prototype. In the article (Mężyk *et al.,* 2011) the authors describe research on the development of a semi-active suspension, in which the controllable element is a shock absorber with a magnetorheological fluid that changes viscosity depending on the

applied uniform magnetic field. The performed numerical calculations of the vehicle quarter model, where the parameters are the relative speed of the shock absorber piston displacement and the intensity of the current flowing through the solenoid, allow to determine the dynamic characteristic of the shock absorber. Selected results of numerical tests show a favorable reduction of acceleration of the sprung mass of the vehicle, subjected to loads in the form of resonant vibrations at a frequency of 1.25 Hz and with the magnetic field of the shock absorber switched on. The author of the publication (Freier, 2005) uses the SAMCEF Mecano finite element analysis software, dedicated to virtual mechanical prototyping, for the dynamic analysis of tracked vehicles. The software allows multi-variant simulations of a parameterized vehicle model. The vehicle parameters define the mass, the geometry and the dimensions of the parts, the mounting points of the control arms of the road wheels and the mutual attachment points of the individual elements of the suspension system. The simulation parameters determine type of ground or dimensions of the obstacle to be overcome, motion parameters (initial speed, acceleration, and deceleration), combat mass of the vehicle, spring and damping characteristic of the suspension elements, static ground clearance and static deflection angle of the control arms of the road wheels. The results of the numerical research are graphs, animations, drawings showing the acceleration values of the driver's seat, the angle of inclination of the vehicle and the reaction force of the road wheels from the ground. In (Tang *et al.,* 2017) model tests were conducted to analyze the turning maneuver of a high-speed tracked vehicle. The tests considered factors such as the deformability of the terrain, the longitudinal distribution of pressures, the location of the center of mass, and the ratio of length to track spacing. The comparison of the results of the model tests with the experimental ones showed the fidelity of the model, which allows to predict the efficiency of the driving of the vehicle. Modeling of a tracked vehicle turning is also described in the article (Zou *et al.* 2018). An unmanned low--speed vehicle is considered in terms of the possibility of accurate, remote control despite the turn using, by assumption, the phenomenon of tracks slipping on the ground. To precisely position the vehicle, the authors proposed a combination of three biaxial accelerometers in MEMS technology (microelectromechanical systems), positioned at an angle of 120º to each other, to measure the longitudinal and angular velocity of the vehicle. The article analyzes the kinematics of the turn while the created mathematical model allows the calculation of driving force, longitudinal and lateral resisting forces, turning moment and turning resisting moment. In the article (Nabagło, 2011) the methods of modeling the construction of tracked vehicles in the program MSC Adams are presented along with the analysis of their advantages and disadvantages. After the review, the author chose the method of accurate representation of the geometry of the chassis elements and presented the next stages of the model research. The final effect of the work are the results of dynamic simulations of the complete model of the tracked vehicle.

Numerical studies should be validated by experimental studies. The following papers present examples of the combination of the two mentioned methods of suspension system quality analysis. In the article (Gniłka, Mężyk, 2017) the authors presented several ways of selecting and identifying the parameters of the tank chassis, including the suspension. Among them are such methods as: mathematical and numerical modeling, experimental research, statistical analyses, including the formation of the objective function and minimization of the parameters important from the point of view of the motion quality of the model. Experimental tests were conducted by means of the photogrammetric method to determine the linear characteristic of displacement, velocity, and acceleration of selected points of the vehicle body. The mathematical model was compared with the experimental results. The parameters to be compared were displacement, velocity, and acceleration of selected points of the hull. To choose the optimal amount of shock absorber damping the analysis of hull inclination changes was conducted. The result of the work was a universal method of selecting the parameters of the suspension of tracked vehicle, such as the track tension or the amount of shock absorber damping. The article (Hryciów *et al.,* 2023) presents the results of field tests of the hydropneumatic strut of an armored personnel carrier on a test stand and describes its mathematical model. The simulation tests revealed the influence of temperature on the value of the static deflection and the coefficient of the spring elasticity of the strut. These findings were confirmed by on-track tests. Significant heating of the strut and a change in the ground clearance under the vehicle were observed during the tests. Intensive operation of the vehicles in the field also affects the heating of the liquid in the shock absorber and, as a result, changes the damping characteristics. Paper (Hryciów, 2022) presents the results of tests of the shock absorber in a wide temperature range and a method for assessing the technical condition based on the recorded characteristics. The paper (Shang *et al.* 2009) presents the advantages of using modern methods of virtual prototyping and numerical modeling in the construction or modernization of tracked vehicles. The authors built a vehicle model, validated it by experimental tests, and used optimization methods to select the stiffness value of the torsion bars. Due to the long service life of military vehicles, an optimal modernization stock should be provided at the design stage. As most of the modernizations of military equipment conducted so far show, this may be related to the increase in the mass of the vehicle and the need to adjust the characteristic of the suspension. In addition, the concept of creating a tracked chassis assumes that it will be used to build various applications (Grabania *et al.,* 2012) with different masses, moments of inertia and location of the mass center, which should also be considered at an early stage of design development. The paper (Allen, Goyder, 2005) presents rig design, experimental procedure and measurement for rotary damper and rubber components, as well as comparison between measured and simulated model response. The aim of the article (Hammad *et al.* n.d.) is to evaluate the characteristic of hydropneumatic suspension

and apply it for the armored fighting vehicle BMP-1. The authors accomplish this through modeling of the hydropneumatic suspension unit mathematically and on the second step validation of the model using MATLAB/SIMULINK. Then, in order to validate the results obtained from the model, the authors conduct experimental research. The conducted research and the proposed unconventional solution result in an improvement in driving quality parameters.

After the prototype of the vehicle has been made, experimental verification of the vehicle should be conducted - testing of the vehicle prototype on obstacle course for tracked combat vehicle. In the article (Levulytė *et al.* 2014) the authors analyze the influence of the road unevenness on the changes of the vibration frequency of various elements of the vehicle suspension structure. On the other hand, in the article (Rybak, 2014) an analysis of the loads acting on the impact-type tracked combat vehicle was conducted. The main sources, such as vehicle movement in uneven terrain, main armament firing, mine or IED explosion, projectile hit, were analyzed qualitatively and quantitatively. The article also presents valuable results of experimental research showing a wide variety of values and directions of loads. The results may be helpful in reducing the impact of loads on the internal equipment of vehicles. It should be emphasized here that the method of mounting the equipment on the hull of the vehicle is especially important, which should increase the resistance of components to impact loads, considering their value, direction, and range of frequencies.

## Requirements for the suspension of high-speed tracked vehicles

The suspension of tracked combat vehicles has to meet a number of very important and complex requirements. The main ones are:

1. Providing the vehicle with good quality of movement (i.e., enabling it to perform effective actions while driving in the entire speed range, e.g., according to (Murphy and Ahmad 1986, *NATO STO/AVT Support Project No. SVK-AVT-16/01. Final Report. Evaluation of In -Vehicle Vibrations and Their Effect on Vehicle Structures and Personnel Health and Performance* 2020), these requirements are formulated as follows:

  - during overcoming single irregularities on the track with artificial obstacles, vertical accelerations affecting the driver $a_z < 2.5\ g$;
  - in tests on unpaved roads and in the field, when driving on selected routes, the power of the vibrations absorbed by a human $P \leq 6\ W$ (power absorbed by the body SAR - Specific Adsorption Rate - is defined as the amount of mechanical energy applied to the human body in the form of vibrations and accelerations per unit of time;

- the period of vertical vibrations of the body $T_z$ should meet the condition $T_z > 0.6\ s$ and the period of longitudinal angular vibrations $T_\varphi$ should meet the condition $T_\varphi \in 1.25 \div 1.4\ s$.

2. Providing the vehicle with high operational safety and long technical life, of which modern methods are more extensively described in (Żółtowski *et al.* 2022), including:

- adequately high unit potential energy value of the suspension;
- the use of springs characterized by high reliability and durability;
- appropriately high strength of the elements subjected to dynamic overloading during the so-called "pressing down" of the suspension;
- effective sealing of movable joints.

3. Sufficiently high resistance to impulse (combat) loads, the source of which may be an enemy's activity as well as one's own (Wiśniewski 2023).

4. Where possible, low weight and dimensions (especially for elements located in the hull).

## Suspension selection for a high-speed tracked vehicle

Modern tracked combat vehicles use individual suspensions with metal spring elements and, increasingly, non-metallic springs. In the first group of suspensions, torsion bars or coil springs are used as spring elements. In the second group, hydropneumatic suspensions are used. They use the springiness of gas, which results in progressive spring characteristic. Thanks to such characteristic, the road wheels near the static equilibrium position obtain a low frequency of vibrations, while when approaching the limit deflection, the suspension increases its stiffness, preventing it from hitting the stroke limiter. Hydropneumatic suspensions can be divided according to the way the hydropneumatic element is located inside and outside the vehicle hull (Fig. 3). The first group includes suspensions with a hydropneumatic element in the form of a hydropneumatic strut. Due to the way it is installed in the vehicle, it is subjected to significant, complex dynamic and shock loads (including the explosion of the mine) during operation. Experience and practice indicate a meaningful change in the spring characteristic at that time, which is shown in Fig. 5.
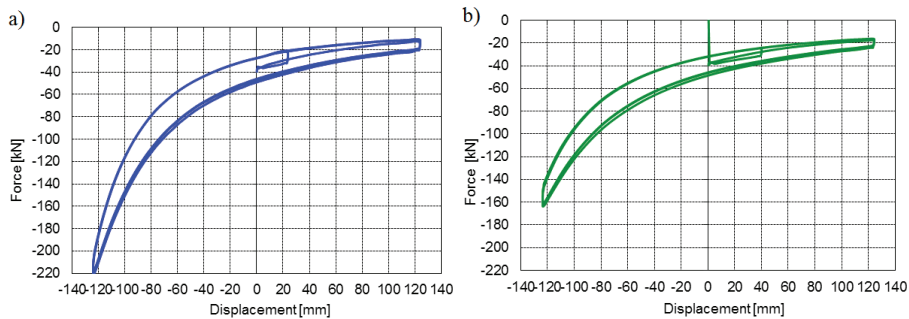
Fig. 5. Spring characteristic of the hydropneumatic column: a) new, b) after operational events

Source: Own study

The second group includes a suspension with a rotary hydropneumatic unit acting as a control arm. Depending on the method of separation of gaseous and liquid medium, elements with a diaphragm or a separating piston are distinguished. The construction of the hydropneumatic element can be single or double cylinder.

## Calculation example

**Concept and selection of basic suspension parameters**

Within the framework of the work a concept of hydropneumatic suspension for a hypothetical high-speed tracked vehicle was developed.

The initial assumptions of the control arm design are as follows: vehicle tare mass – $m = 25\ t$, number of road wheels – $n_k = 12$ (6 on each side), maximum ground clearance – $h = 500\ mm$, minimum ground clearance – $h_{min} = 150\ mm$, dynamic stroke of the road wheel – $f_{kdyn} = 350\ mm$, static stroke of the road wheel – $f_{ks} = 200\ mm$, diameter of the road wheel – $d_k = 675\ mm$, length of the control arm – $l_w = 475\ mm$.

A structural sketch of a single suspension element - a control arm with an internal hydro-pneumatic spring-damping element - is shown in Fig. 6. The control arm of the first wheel with the highest load was used for the calculations. The first road wheels are the first to go over the obstacle (for other wheels, the track smooths out the unevenness).
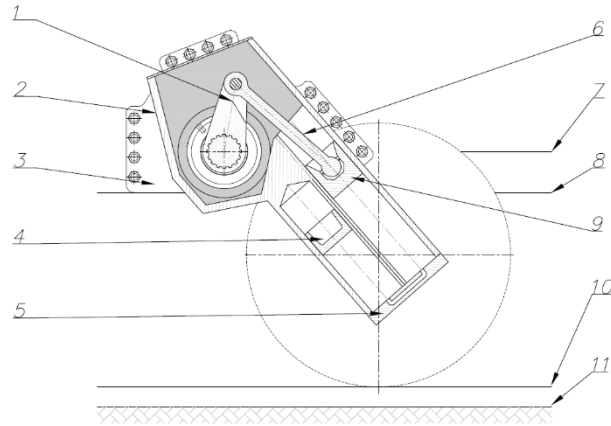
Fig. 6. Structural sketch of the control arm: 1 - crank, 2 - control arm body, 3 - control arm mounting plate, 4 - separating piston, 5 - shock absorber module, 6 - connecting rod, 7 - level of the pivot axis of the control arm, 8 - bottom of the vehicle hull, 9 - main piston, 10 - upper surface of the track, 11 - ground level.

Source: Own study

The suspension consists of a control arm mounting plate 3, which is bolted to the tracked vehicle hull and structurally forms a single unit with the control arm axle. The control arm body is mounted on tapered roller bearings in a back-to-back arrangement (O) on the control arm axle. Crank 1 is fixed to the splines on the control arm axle. The crank 1 is connected to the connecting rod 6 by a cylindrical joint, while the connecting rod 6 on the other side is connected to the main piston 9 by a ball joint. Hydraulic fluid flows through calibrated holes and valves of the shock absorber module 5 to the parallel cylinder. Above the hydraulic fluid chamber there is a separating piston 4, which separates it from the nitrogen-filled gas chamber.

The reaction of the gravitational force acting from the ground through the track to the road wheel of the vehicle causes the control arm body to rotate upward. The rotating body reduces the volume between the main piston and the damper module, causing the fluid to compress and flow into the second cylinder. The flowing fluid moves the separating piston, which compresses the gas. As the reaction under the road wheel decreases, the expanding gas by analogy causes the control arm to rotate downward.

Calculations of the characteristic of the hydropneumatic suspension unit

Assuming an even distribution of the vehicle's mass on each road wheel, the ground reaction acting on the road wheel axle is equal to the static load – $F_{stat}$:

$$F_{stat} = \frac{M \cdot g}{n_k} \tag{1}$$

where: $M$ – mass of the vehicle [kg], $g$ – acceleration due to gravity [m/s$^2$], $n_k$ – number of road wheels.

From the equation of the moments of the forces acting on the axis of the road wheel and on the face of the main piston relative to the axis of the control arm, it is possible to calculate the force $F_4$ acting on the main piston. Knowing the force $F_4$ and the area of the piston $S$, the working pressure in the cylinder $p$ is equal to:

$$p = \frac{F_4}{S} \tag{2}$$

Changes in the volume of the gas chamber at twelve positions of the control arm have been determined structurally. Selected positions of the control arm during operation are shown in Fig. 7.
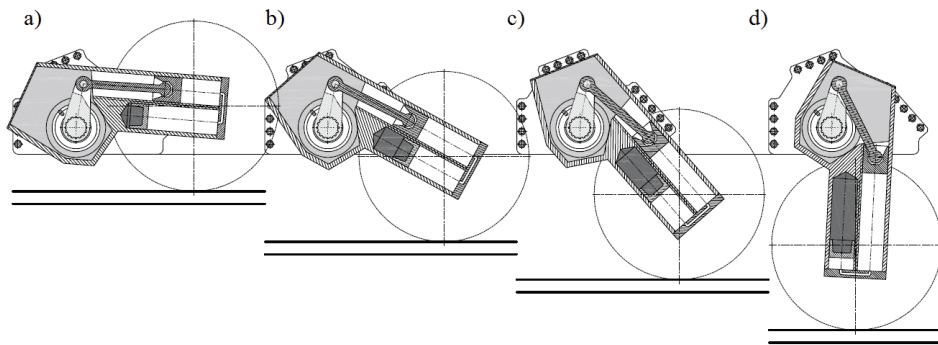


Fig. 7. Selected positions of the control arm with the volume of the gas chamber highlighted (dark grey): a) maximum dynamic deflection, b) intermediate position, c) static position, d) position corresponding to lifting the road wheel from the ground
Source: Own study

On the basis of preliminary calculations, the internal diameter of the cylinder liner and pistons was assumed – $d_c = 100\ mm$, the length of the main piston – $l_t = 120\ mm$, the length of the separating piston – $l_{t2} = 70\ mm$. The gas pressure in the chamber of the control arm loaded with a static load is $p = 5{,}7\ MPa$.

Changes of the pressure of the piston $p$ w zaledepending on the volume $VV$ are determined by the thermodynamic transformation taking place in the gas chamber. This transformation is the closest to the adiabatic transformation (no heat exchange with the environment) (Walentynowicz 2009), its course is described as follows:

$$p \cdot V^n = const \tag{3}$$

where: $n$ - polytropic constant depends on the type of thermodynamic transformation: isobaric transformation $n = 0$, isothermal transformation $n = 1$ , isentropic transformation (constant entropy of the system) $n = k$, isochoric transformation $n = \infty$.

The transformation taking place in the control arm is reversible (constant entropy of the system), therefore the polytropic constant will be equal to $n = k$. The constant $k$ win this case depends on the type of gas used in the hydropneumatic element, and more precisely on its heat capacity. A commonly used gas in hydropneumatic suspension is nitrogen, for which the polytropic constant at a temperature of $300\ K$ is equal to $n = k = 1{,}4$.

In Fig. 8. the dependence of the force acting on the main piston on its stroke is shown, which results directly from the springiness of the gas.
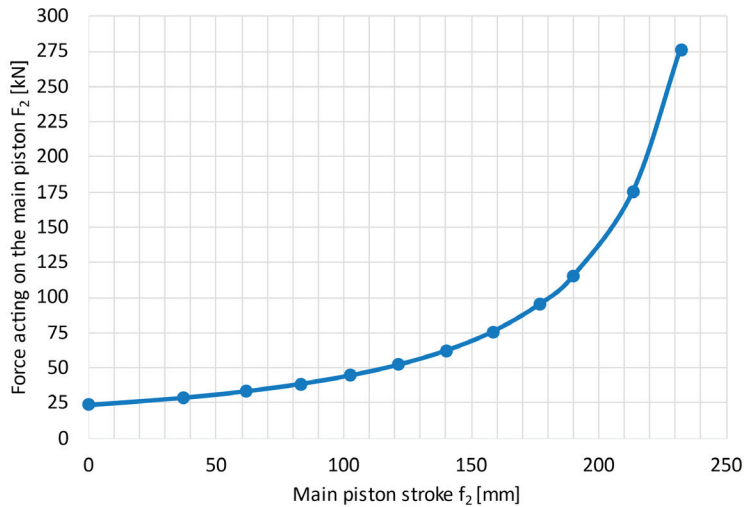


Fig. 8. Dependency graph: force acting on the main piston as a function of its stroke
Source: Own study

Using the above information, the spring characteristic of a single element of the hydropneumatic suspension was determined. It is determined by the dependence of the spring force $FF$ on the stroke of the road wheel $f_k$, and thus $F = \varphi(f_k)$. The characteristic curve is shown in Fig. 9.
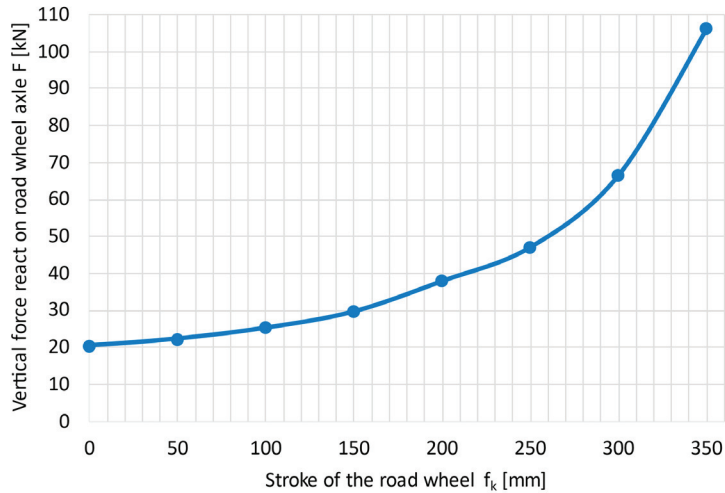
Fig. 9. Spring characteristic of a hydropneumatic spring element
Source: Own study

The calculations assumed:
-    ideal gas,
-    incompressible hydraulic fluid,
-    no heat exchange of the heating control arm with the environment.

The above made it possible to adopt an adiabatic transformation in the model, to omit the internal friction of the gas and the hydraulic fluid, as well as the viscous friction during the flow of the fluid through the shock absorber module.

In fact, the spring characteristic of the hydropneumatic unit is not reversible, which would be shown in the diagram by changing the shape to a hysteresis loop. The resulting characteristic is progressive, which is advantageous in terms of achieving high smoothness and driving comfort.

The suspension with the presented characteristic has a low stiffness around the static equilibrium position and it increases with increasing wheel stroke. As a result, the potential energy of the suspension's springiness is increased in comparison with suspensions on torsion bars. This results in an increase in the unit potential energy of the suspension $\lambda_p \lambda_p$, which is given by the relationship:

$$\lambda_p = \frac{E_p}{G} = \frac{2 \cdot n_k \cdot k_{ki} \cdot f_{km}^2}{M \cdot g} \ [m] \tag{4}$$

where: $E_p$ – potential energy of the suspension, $G$ – weight of the vehicle, $n_k$ - the number of road wheels on one side corresponding to the number of elastic elements of the suspension, $k_{ki}$ - stiffness of the elastic element of the suspension, $f_{km}$ - maximum stroke of the road wheel, $g$ - acceleration due to gravity, $M$ - sprung

mass of the vehicle (if $M \nearrow$ that $\lambda_p \searrow$). The physical meaning of the coefficient $\lambda_p$ ($\lambda_p = h$) is shown in Fig. 10. Unit potential energy of the suspension $\lambda_p$ is the height from which the vehicle can be dropped, at which the suspension is subjected to reach maximum deflection, but without hitting the stroke limiter. Modern high-speed tracked vehicles are characterized by the value of the $\lambda_p$ coefficient in the range of 30 - 75 cm.
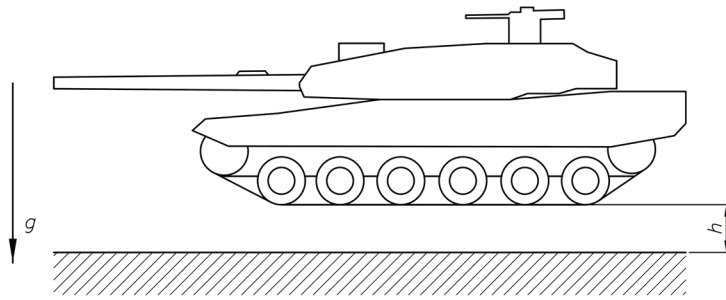


Fig. 10. Diagram showing the physical sense of the unit potential energy of the suspension $\lambda_p$
Source: Own study

# Initial design of the control arm, numeric analysis

### Numerical model of the control arm

Using the Dassault Systèmes CATIA V5 design support software (according to the concept in Fig. 6) a 3D model of the hydropneumatic control arm was created, as shown in Fig. 11 and Fig. 12.
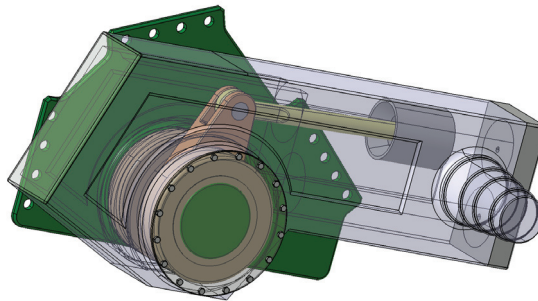


Fig. 11. Physical model of the hydropneumatic control arm
Source: Own study

**Maximum control arm loads (calculated)**

A principal issue in the design of the elements guiding the road wheels (control arms) is the determination of the loads acting during off-road driving. The most severe driving conditions have been considered, generating maximum loads from vertical and lateral forces. The maximum vertical forces $F_{max}$ transmitted by the control arm occur when the control arm hits the stroke limiter. The control arm then carries loads approximately 8-10 times greater than the static load $F_{stat}$:

$$F_v = F_{max} = (8 - 10) \cdot F_{stat}.$$ (5)

The largest lateral force $F_H$ $F_H$ occurs when driving on a slope and turning the vehicle toward the slope:

$$F_H = \frac{1,8 \cdot \mu \cdot G}{4}$$ (6)

where: $\mu$ - coefficient of turning resistance, $G$ - gravitational force of the vehicle, 1,8 – the highest calculated value of the *L/B*, agility index, where *L* – is the length of contact of the tracks with the ground, *B* - is the track spacing.
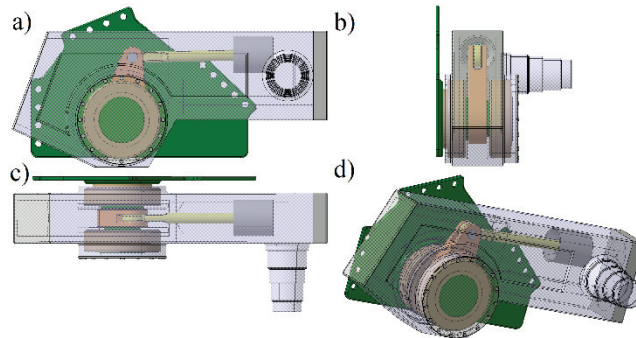


Fig. 12. Physical model of the hydropneumatic control arm: a) side view, b) front view, c) top view, d) isometric view
Source: Own study

**Selection of construction material**

Due to the considerable number of materials with different properties, material selection consists of finding a compromise between operational and technological properties (workability, formability, weldability, hardenability), strength and economic properties. This problem is not simple and there is no single method of

material selection. Material selection is often based on similarity to existing design solutions. The selection is based on, among other things:

- expected operating conditions and types of loads;
- type of deformations (Young's modulus, Kirchhoff's modulus, Poisson's ratio, allowable stresses are selected);
- working environment (attention should be paid to corrosion resistance and combination of component materials);
- operating temperature (attention should be paid to heat resistance, creep, relaxation);
- the complexity of the shape of the element (attention should be paid to processing conditions);
- electrical functions (resistance, electrical conductivity is selected);
- thermal functions (thermal conductivity);
- the number of produced units (pay attention to the economy of production and purchase costs).

For the adopted scheme of the control arm and preliminary recognition, the selection of materials for individual elements of the control arm was made. For the most heavily loaded elements: control arm mounting plate, connecting rod and crank, 35HM, 34CrMo4 alloy structural steel for loaded parts of machines and devices with yield strength – $R_e > 800$ MPa, tensile strength – $R_m = 1000 - 1200\ MPa$ and softened hardness $< 241\ HB$ was chosen. For other elements, higher quality structural steel with yield strength – $R_a = 420$ MPa, limit of tensile strength $R_m = 710 - 880$ MPa and hardness $255\ HB$ was chosen.

**Strength analysis of the control arm structure**

Initial strength calculations were performed using FEM in the displacement formulation. The strength analysis was conducted using CATIA V5 software. The load was a vertical force acting on the axis of the road wheel in its plane of symmetry with a value 9 times greater than the static load:

$$F_V = F_{max} = F_{stat} \cdot 9 = 183.6\ kN \tag{7}$$

The calculations made it possible to determine the state of stress and deformation in all significant elements of the structure. Stresses in all elements of the control arm were assessed.

Sample results of the calculations are presented in the form of colored bitmaps in the figures. The distribution of reduced stresses in the structure and components

of the control arm is shown in Figs. 12-15. Deformations of the control arm body structure are shown in Fig. 17.
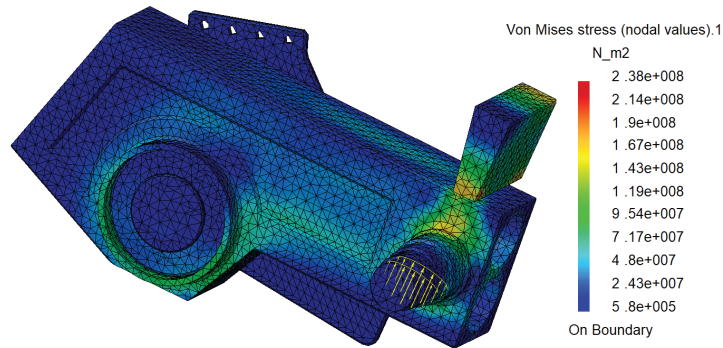


Fig. 13. Distribution of reduced stresses according to the Huber-Mises hypothesis in the control arm body and the stroke limiter during the hit to the stroke limiter
Source: Own study

Fig. 13 shows that the reduced stresses in the body of the control arm occurring at the moment of hitting the stroke limiter under full load, at the area where the axis of the road wheel meets the plane of the body of control arm, do not exceed the values in the range of 167÷190 MPa. Their distribution in the load zone is uniform and does not cause stress accumulation.
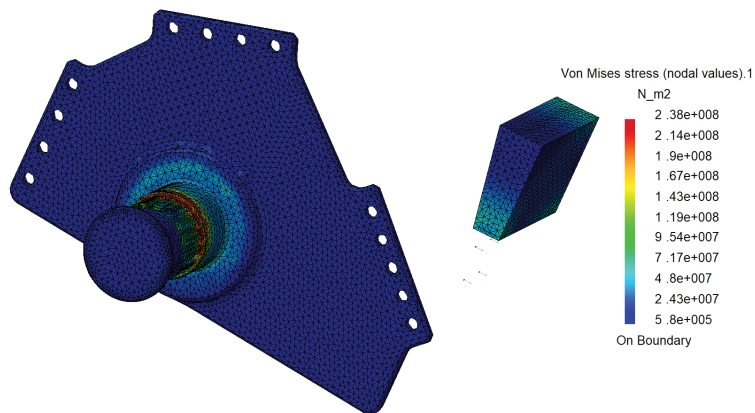


Fig. 14. Distribution of reduced stresses in the control arm mounting plate
Source: Own study

Analyzing the distribution of stresses in the control arm mounting plate (Fig. 14), it can be seen that the highest stresses occur on the control arm rotation axis at the area of contact between the crank and the mounting flange. The stresses in the analyzed zone do not exceed values in the range of 190-214 MPa.
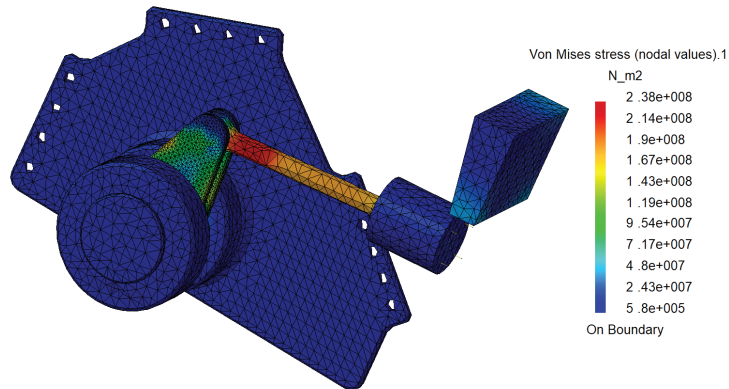


Fig. 15. Distribution of reduced stresses in the internal elements of the control arm
Source: Own study

Analyzing the distribution of internal stresses in the elements of the control arm in Fig. 15, it can be seen that the connecting rod is the most heavily loaded. The highest stresses occur at the area where the cross-section of the connecting rod narrows, to enable it to cooperate with the crank. The maximum stress value in the tested profile is 238 MPa. Despite the fact that the permissible stresses are not exceeded, it is necessary to consider changing the geometry of the connecting rod by using a larger cross-section in the part of the connecting rod cooperating with the crank and a smoother transition to a circular cross-section in the part of the connecting rod cooperating with the main piston.

Fig. 16 shows that the highest stresses of the crank occur at the cross-section change in the vicinity of the revolute joint and do not exceed the values in the range of 214÷238 MPa. Such a high stress value is caused by too low density of the finite element mesh, but also by the presence of a geometric notch. Even though the permissible stresses are not exceeded, it is necessary to consider the use of a larger rounding radius at the point where the highest stresses occur.

The analysis of the level of reduced stresses showed that the permissible stresses for the selected materials were not exceeded.
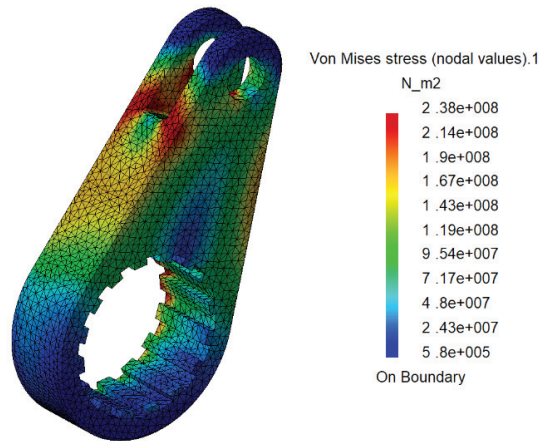
Fig. 16. Distribution of reduced stresses in the crank
Source: Own study

In the case of the hydropneumatic control arm design, the condition of not exceeding the permissible stresses was assumed as a condition of sufficient reliability. The displacements of the maximum mesh nodes of the tested object were not analyzed in terms of maintaining the permissible deformation level. The deformations of the control arm body are shown in Fig. 17. The point of maximum deflection of the control arm body is inside the force field. The value of the maximum deflection at this area is 0,17 mm.
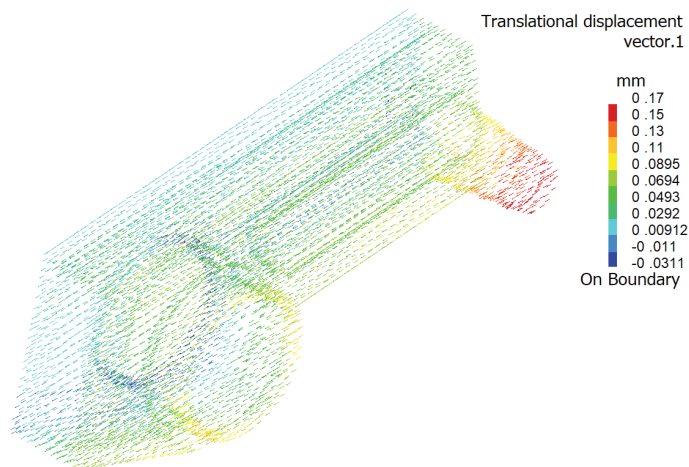


Fig. 17. Deformation of the control arm body
Source: Own study

As a result, the designed hydropneumatic element of the suspension was used in comparative model tests of a preliminary nature. The original DYDZPG software was used to compare the use of hydropneumatic suspension and mechanical suspension on torsion bars. The value of the vertical accelerations acting on the driver (the person furthest from the center of gravity of the vehicle - Fig. 18) is determined from the following relationship:

$$a_{zk} = a_{zmax} + l_0 \ddot{\varphi}_m \qquad (8)$$

where: $a_{zmax}$ – maximum value of the acceleration of the vertical vibrations of the center of mass of the vehicle, $l_0$ – distance of the driver's seat from the center of mass of the vehicle, $\ddot{\varphi}_m$ – maximum value of the acceleration of the longitudinal angular vibrations. An exemplary course of vertical accelerations of the center of mass of the body and the driver's seat for the compared suspension types is shown in Fig. 19 and Fig. 20.
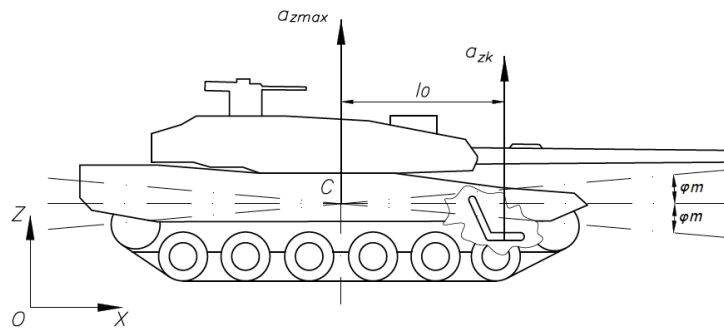


Fig. 18. Sketch of the vehicle model
Source: Own study

With the hydropneumatic suspension, there is a clear reduction in the level of loads acting on the vehicle and its driver.
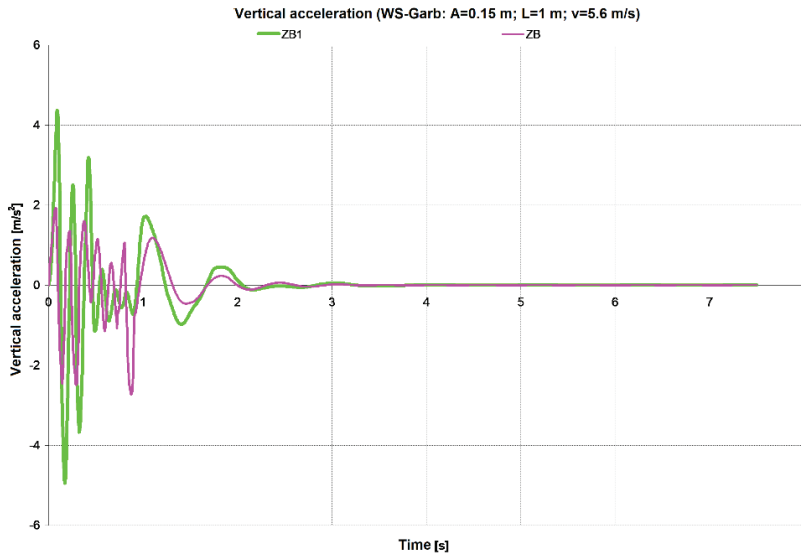
Fig. 19. Vertical accelerations of driver's seat (ZB) and vehicle center of mass (ZB1) for torsion bar suspension
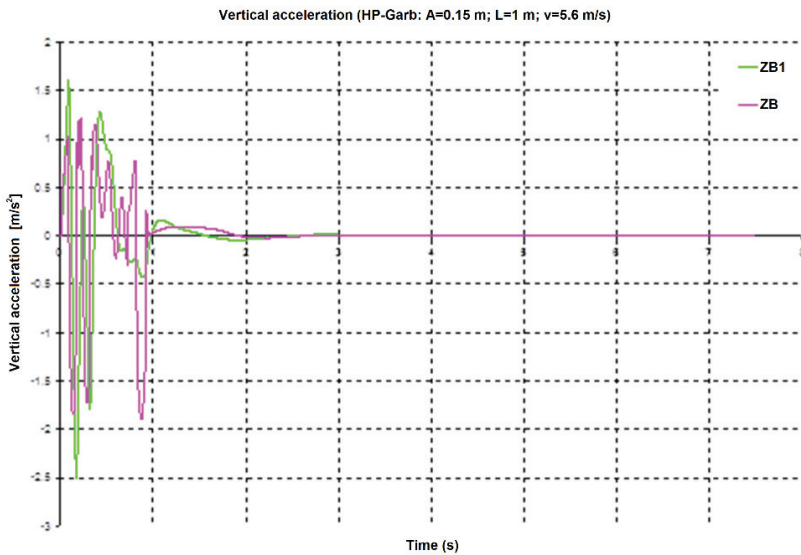
Source: Own study



Fig. 20. Vertical accelerations of the driver's seat (ZB) and the vehicle's center of mass (ZB1) for hydropneumatic suspension

Source: Own study

## Conclusions

When designing a new combat vehicle or modernizing an existing one, it is necessary to meet the high demands of the current and future battlefield and operating conditions.

Hydropneumatic suspension is increasingly used in modern high-speed tracked vehicles. It has a number of advantages:

**First**. It meets the requirements for high smoothness of tracked vehicles due to the possibility of obtaining high potential energy of the suspension, progressive spring characteristic obtained in a straightforward way thanks to the course of gas compression and large lift of the road wheels.

**Second**. By introducing an additional system that controls the amount of hydraulic fluid and gas, as well as the throttle valve of the shock absorber, additional benefits can be obtained, such as: adaptation of the spring characteristic of the suspension (from regressive to progressive) to the current traction conditions, the ability to change the ground clearance and the lateral and longitudinal inclination, as well as locking the vehicle suspension, the ability to adjust the center of springiness of the suspension to the changing mass center of the vehicle, depending on the application (type of vehicle), armor and additional equipment. These modifications extend the vehicle's capabilities with new features that are useful on the battlefield and significantly increase the crew's comfort, thanks to the ability to adapt the suspension characteristic to the current driving conditions, which affects survivability.

**Third**. By using a control arm with a built-in hydropneumatic element, we obtain modularity and unification of the structure that simultaneously performs all the suspension functions (guidance, suspension, vibration damping), we also gain ease of use, repair and replacement of the control arm (integration of the control system with the hydraulic track tensioning mechanism and introduction of a replacement mode of the control arm or track, which causes the hydraulic fluid to be pumped out of a hydropneumatic component or components of one side of the vehicle and reduces the tension of the track), in addition, we do not interfere with the internal space of the vehicle body.

**Fourth**. Improvement of the vibration damping compared to the classical suspension, by using a shock absorber on each road wheel of the vehicle.

An obstacle to the widespread use of hydropneumatic suspension in heavy tracked vehicles, apart from the cost, may be the occurrence of high pressures of the working medium, which make it difficult to achieve the required tightness of the hydropneumatic element.

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