SUBSTANTIATION OF THE TESTS CONCEPT ON DETERMINATION OF RESOURCE INDICATORS OF POWER ELEMENTS OF SPECIALIZED ARMORED VEHICLES

The article provides information on the concept of assessing the resource of power elements of the design of a specialized armored vehicle during testing and its adjustment to the standards of NATO member states. It involves the implementation of simulated mathematical modeling with an evaluation of the static and dynamic characteristics of the vehicle's power structure. When simulating fatigue damage of a structure, the hypothesis of a linear damage summation rule is used to more reliably determine the life of a vehicle. During field tests the use of modern hardware and software for measuring the actual characteristics of loading a car when driving on different types of roads is proposed.

Keywords: specialized armored car, power elements of construction, modeling, resource.

Introduction. In recent years, the State Scientific Research Institute of Armament and Military Equipment Testing and Certification has acquired considerable experience in testing vehicles for military purposes. One of the problematic issues, which is not always unambiguously addressed during the tests, is the justification and confirmation of the assigned resource indicators (mileage, service life) of automotive samples [1]. This concerned the choice of the car's mileage during the tests, the quality of the roads and the percentage distribution between them. Today, manufacturers do not have a single approach to justify and confirm the declared resource indicators of special vehicles.

An important characteristic of the machine's performance, which affects its resource (service life) during the life cycle, is the fatigue of the material [2].

The theory of fatigue is mostly empirical. This means that the process of microcracks, which eventually form macroscopic cracks in the material, are not taken into account in the analytical equations [3–4]. Due to the large scatter of data during the tests, the properties of fatigue resistance are processed by statistical methods. Almost all mathematical equations of the theory of resistance to fatigue are those that describe the test results. Therefore, the verification of the actual characteristics of fatigue resistance is usually carried out in the process of testing [1, 5].

Bench and road tests are used to assess the reliability of automotive equipment. Bench tests are performed on units and parts and are designed to assess the static strength and fatigue resistance of parts, as well as wear resistance of joints. Road tests are carried out on the vehicle as a whole and as divided into operational, landfill and special.

Operational (military) tests provide the most objective information about the reliability of the car, but they are characterized by a long duration. Therefore, it is advisable to assess the durability of the car with the help of tests, the duration of which is significantly reduced compared to operational tests by strengthening the load modes of the car in a specialized landfill. The mileage of one kilometer on a special sections of the road test site may be equivalent to the mileage of 20 km on conventional road.

The load of the frames (capsules) of specialized vehicles is mostly determined by the vertical dynamic loads from the unevenness of the road. When driving on paved roads in the vast majority of symmetrical bending loads. When driving on field dirt roads or off-road, oblique symmetrical loads prevail, which twist the frame (capsule) of the car.

The transition of Ukraine to NATO standards requires a new concept of testing to determine the resource indicators of the power elements of the vehicle design, which consists in wide use of simulation mathematical modeling of static and dynamic characteristics of the power structure, reducing test time by increasing load modes, improving the reliability of vehicle resource indicators [6].

The purpose of the work is to develop a concept for determining and evaluating the resource performance of automotive power elements during testing and bringing it in line with the standards of NATO member states.

**Presenting main material.** The following factors are necessary to be taken in account in order to create the reliable design of the vehicle (fig.1):

- the diversity of consumers, ie the nature of the vehicle operation;
- variety of road surfaces, that causes different levels of workload on the structure;
- dispersion of construction material properties;
- dispersion of technological processes at creation of the specialized armored vehicle.

![Diagram](image)

Fig.1. Taking into account a variety of factors in the design of the car

The following specialized armored vehicles (fig.2) were presented for testing at the institute between 2015 to 2021: KrAZ “Shrek”, KrAZ “Feona”, “Bars-8”, “Kozak-01”, “Kozak-2”, “Kozak-2M1”, “Renault Sherpa Light Scout”, “Novator”, “Ontsilla”, “Dozor-B”, “Triton”, “Varta” and others.

These were mainly defining departmental tests that did not involve assessing compliance with the full range of requirements. At their carrying out only the basic tactical and technical characteristics which are declared by the manufacturer are checked. Only the car “Kozak-2” passed state tests. During the state tests it was established that the issue of confirmation of the set resource indicators is not given enough attention.
Fig. 2. Specialized armored vehicles:
Consider the characteristic designs of the bodies of specialized armored vehicles fig.3.

The design of the capsule consists of the following main elements: steel frame; armor outer skin; internal covering. A layer of special non-rigid material (such as fiberglass) is placed between the outer and inner cladding.

As it is seen from the analysis of vehical body structures, a characteristic common feature is the presence of a steel frame, which when moving the vehical receives the load from the weight of the armor plates and transmits these loads to the vehicle frame.

During operation, the specialized armored vehicle is subject to loads arising during its movement on the road surface. These loads are usually random and can be divided into random and deterministic. Determining the magnitude and directions of the load – a rather difficult task, so when calculating the vehicle from the whole set take into account the loads that occur in extreme operating conditions.

The creation of a mathematical model of the load on the power elements of the structure of a specialized armored vehicle will be considered on the example of the car “Kozak-2”. The main power of the capsule structure, which absorbs the force load, is the frame and the outer skin. Therefore, it is possible to limite the force calculations by using 3D-model only of the force part of a capsule (fig.4).

Fig.3. Capsules of specialized armored vehicles “Kozak-2” (a) and “Novator” (b)

Fig.4. Calculated model of the capsule

Fig.5. Stress-strain state of the capsule
Modeling of the stress-strain state of the capsule (fig.5) allows to obtain distributed fields of mechanical stresses in the material and deformations of the structure.

Static calculations of armoured vehicle bearing systems for symmetrical (bending), obliquely symmetrical (torsion) and side loads are usually performed for such extreme deterministic loading cases: vertical symmetrical loading on all wheels; vertical non-symmetrical load (wheel crash and wheel hanging); horizontal load when moving in a curved trajectory; wheel collision on a stepped obstacle. The sum of these loads can be replaced by the sum of the symmetrical and obliquely-symmetric forces causing the bending and torsion of the bearing system relative to the longitudinal axis.

Together with quasi-static loads, the category of extreme loads includes dynamic loads that occur during impact and low-frequency resonance. Loads arising from the impact, as a rule, have a short (pulse) effect. Therefore, the consequences of such action are most evident in the local area of the car.

Depending on the profile of the road surface, as well as the driving conditions of a specialized armored vehicle, oscillations with frequencies close to resonant can occur. These phenomena are especially dangerous for bearing systems of cars at frequencies 0 ... 5 Hz. If there is a resonance, the destruction of the elements of the car is possible, including the load-bearing system due to excessive dynamic loads. Therefore, an important area of assessment of cars in the tests is the study of possible resonant phenomena.

Multicyclic fatigue is one of the reasons for the limit states of structural elements of cars. It is the limit of fatigue of a particular structure is determined by the resource of the power elements of the structure of a specialized armored vehicle. Fatigue injuries often occur when exposed to variable loads that exceed the endurance limit.

Based on the analysis of different models of damage accumulation, it is established that the linear hypothesis of summation of tired injuries, which depends on the amplitude of alternating stresses, is most often used. The method of estimating and forecasting the residual resource according to this hypothesis is known. As a criterion for achieving the limit state that determines the durability of the structure, a critical set of existing defects and accumulated damage is taken [1, 5]. The study of the processes of generation and development of damage is an urgent problem in the calculations of the fatigue strength of structures under non-stationary loading.

The mechanical load of the car structure is due to its loading, as well as shock and vibration loads acting from the road surface. By its nature, the load of the car structure can be: pulsed, stepped, continuous or combined. In addition, the type of load of the car structure is divided into deterministic and random. In turn, the random load can be stationary, ergodic, wide- and narrowband. Therefore, in the general case, the process of loading the car when driving on a particular type of road can be considered a broadband stationary ergodic random process.

The characteristics of the mechanical load on the car structure can be assessed by the value of the acceleration of the center of mass of the car or the acceleration of any part of the car. The acceleration can be expressed in \(m/s^2\) or in relation to the acceleration of free fall \(g\), i.e. in overload. The main indicators of vibration load are the rms value of the overload, which is measured in units of \(g\), and the value of the spectral density, which is measured in the following units: \(g^2/Hz\).

It should be noted that in the course of research on the load of the car structure it is possible to detect certain regular (periodic) loads. At periodic loads between frequency, displacement, speed and overload there is a clear dependence on each other and, with two known, such as frequency and overload, the rest can be calculated. Since, as a rule, vibration displacements and vibration overloads are normalized at certain frequencies, the formula should be used to calculate their relationship:

\[
n = \frac{I f^2}{250},
\]

\(n\) – overload, units; \(l\) – displacement, mm; \(f\) – frequency, Hz.
The constant component of the vehical load depends on its weight. In addition, when assessing the forces acting on a particular element of the vehicle, should be borne in mind that these forces also depend on the overload and weight of the vehicle.

Specialized armored vehicles are operated in different road conditions. At the same time, it is extremely difficult to comprehensively assess all of the variety of the road surfaces on a car, especially if we take into account that depending on the season and the specifics of the region, the same type of roads may have different characteristics. Therefore, when creating and operating wheeled machines, the assessment is carried out not on the complex action, but on its individual components. The main components of the action are: resistance to movement, adhesion to the bearing surface, micro- and macro-profiles of the road surface. The load on the structure power elements of the armored vehicle, mainly depends on the micro and macro profiles of the road surface.

The primary abstraction of road bumps is the road surface. This abstraction is obvious for a low-deformability road, a specific section of which is a profile implementation, and the set of such implementations of a road profile as a random process. The profile of the road depends on the choice of section, so it is usually carried out on the track.

The road profile is divided into three components: macroprofile, microprofile and roughness. The macroprofile, consists of long smooth irregularities (wavelength of 100 m and more), practically does not cause oscillations of the wheeled machine, but significantly affects its traction and dynamic performance. The microprofile consists of irregularities (wavelength from 10 cm to 100 m), which significantly affect and determine the performance of the armored vehicle. Roughness (wavelength less than 10 cm) is smoothed by tires and does not cause significant vibrations of the vehicle, but affects the performance of the tires.

Therefore, in the future we will consider the microprofile of the road (as one of the main sources of perturbation), thus should be represented as a continuous function of changes in the height of irregularities during the path, followed by transformation into a time function. For the possibility of analysis and modeling, the microprofile of the road is presented in the form of an ergodic Gaussian random process. The normalized correlation function of the road microprofile (Fig. 6) can be described by analytical dependence:

$$\rho_q(l) = \sum_{i=1}^{n} A_i e^{-a_i l} \cos(\beta_i l),$$

$$Q_q(l)$$

Fig.6. Normalized correlation function of the microprofile of the surface of roads of different types:
1 – asphalt concrete; 2 – paving; 3 – soil
The standards MIL-STD-810G of the Ministry of Defense of the United States of America, NATO-STANAG 4370, and also in the VST 01.055.005-2021 – VST 01.055.013-2021 accepted in Ukraine use approximately the same statistical way of the description of a road microprofile. However, the load distribution on the car along the vertical, transverse and longitudinal axes is additionally distinguished. Examples of statistical characteristics of car load when driving on field dirt roads in accordance with accepted standards are shown in fig.7.

Typical phases of operation of a specialized armored vehicle are storage in specialized hangars (boxes), transportation to advanced bases (landfills), operation of the vehicle for its intended purpose, including storage in open areas.

Fig.7. Spectral density of vibration (a, c, e) and probability distribution of vibration amplitude (b, d, f) on vertical, transverse and longitudinal axes (respectively)

At all stages of operation on the elements of a specialized armored vehicle, in addition to the load from the road profile, there are climatic factors that affect the characteristics of fatigue strength of structural elements, namely: moisture and water (rain), temperature changes, icing, solar radiation. The parameters of these factors, which must be taken into account when designing a car, taking into account the climatic region where its operation is planned, are given in the standards MIL-STD-810G, NATO-STANAG 4370, VST 01.055.007-2021 and VST 01.055.010-2021. The action of these factors leads to the destruction of the protective (paint or other) coating and subsequent corrosion of the power elements of the structure of a specialized armored vehicle.
When the metal is in a corrosive environment for some time, the limit of its endurance decreases, and the structure as a whole is no longer able to withstand the normal stresses for it. Structural steels at the test base of $2 \cdot 10^7$ cycles reduce the endurance limit in atmospheric corrosion to 20%, under the influence of fresh water twice, under the action of sea water four times in comparison with the endurance limit in dry air. Stainless steels usually have higher corrosion and fatigue strength. Preferably, the stronger the steel, the more its endurance limit in a corrosive environment decreases. For example, for steel with a strength limit of 1000 MPa, the endurance limit is the same as for steel with a strength limit of 400 MPa.

The nature of fatigue crack growth depends on many operational factors. Thus, the asymmetry of the cycle and the frequency of loading – one of the main indicators of operating conditions that affect the kinetics of critical growth of fatigue cracks in structural materials. This effect is also exerted by various forms of load cycles, temperature, working environment. In turn, the nature and intensity of the environment are determined by the characteristics of the system “material-environment” and the conditions of cyclic loading – the value of the stress intensity factor, asymmetry, frequency and shape of the load cycle.

Chemical corrosion of metals is the interaction of a metal with a corrosive environment, which is believed that the oxidation of the metal and the reduction of the oxidant from the corrosive environment takes place in one act. A characteristic feature of chemical corrosion is the formation of products directly on the surface that is exposed to the oxidant. Electrochemical corrosion of metals is also the interaction of metal with a corrosive medium – an electrolyte in which the ionization of metal atoms and the reduction of oxidant from the corrosive medium are divided in space, through several successive stages, and their velocities depend on the electrode potential of the metal.

Isolation of metal from the action of corrosive environment can be provided by the application of metal coatings, painting, plastic or ceramic coating, sealing, insulation (PVC), the application of temporary protection (oil, grease compositions).

The ability of materials to resist fracture at re-alternating stresses is provided by the durability of the material. Fatigue failure is observed with repeated loading of one sign (from zero to maximum) or with repeated loading, which changes periodically not only in magnitude but also in sign (alternating loads), when the durability of the material is affected by both repetition and variability of load (and both symmetrical and asymmetrical load). Alternative stresses are not enough for fatigue failure. It is necessary that the stresses have the appropriate value. The maximum stress at which the material is able to withstand any number of repetitions of loads without failure is called the endurance limit. The endurance limit is determined experimentally on the appropriate test machines by testing a batch of samples of this material in the amount of not less than 6–12 units. In most cases, the stress variables that cause fatigue failure are a function of time $\sigma = f(t)$ with period $T$. The sum of all stress values for one period is called the stress cycle. The main characteristic of the cycle is the coefficient of asymmetry of the cycle:

$$R = \frac{P_{\text{min}}}{P_{\text{max}}}$$  \hspace{1cm} (3)

$P_{\text{min}}$ – minimum voltage value; $P_{\text{max}}$ – maximum voltage value.

There are also the average voltage of the cycle:

$$P_c = \frac{P_{\text{max}} + P_{\text{min}}}{2}$$  \hspace{1cm} (4)

and cycle amplitude:

$$P_a = \frac{P_{\text{max}} - P_{\text{min}}}{2}.$$  \hspace{1cm} (5)
The most dangerous cycle is the so-called symmetric cycle, when

$$P_{\text{max}} = -P_{\text{min}}.$$  \hspace{1cm} (6)

With a symmetrical cycle $P_c = 0$ and $R = \frac{P_{\text{min}}}{P_{\text{max}}} = -1$.

The limit of endurance in a symmetrical cycle is indicated $P_{-1}$.

For ferrous metals (steel, cast iron, etc.) in engineering practice for the test base take 10 million cycles, for non-ferrous metals (copper, aluminum and others) – the test base is taken 5–10 times more than for ferrous metals.

In some cases, especially for colored materials, the fatigue curve in the coordinates $N$, $P$ slowly goes to the asymptote, so the test base should be chosen much larger (fig.8) [7–9].

The calculation of the resource of a complex structure is performed using the theory of linear summation of damages, according to which it is assumed that from repeated loads the structure collapses after it accumulates in the irreversible form of some deformation energy. It is believed that fatigue damage to the structure from loads of different levels are independent of each other and are linearly added.

![Fatigue Curve](image)

**Fig.8.** Two types of material behavior under cyclic loading

Based on this theory, the resource is calculated by the formula:

$$T = \frac{1}{\eta \sum_{i=1}^{\nu} \frac{N_i}{N_i}},$$  \hspace{1cm} (7)

$n_i$ – the number of load cycles of this level, acting on the structural element for a certain period of operation;

$N_i$ – the number of load cycles of the same level required to destroy this structural element;

$\nu$ – the number of individual levels (degrees) of loads;

$\eta$ – reliability factor according to;

$$\eta = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_4 = 5.4,$$  \hspace{1cm} (8)

$\eta_1 = 1.0$ – takes into account the conformity of the test program of the part to the fatigue nature of the actual loads in operation;
\[ \eta_2 = 1.2 \] – takes into account the degree of safety of destruction, if possible, the detection of fatigue damage from the beginning of its development;

\[ \eta_3 = 1.5 \] – takes into account the range of experimental materials on the recurrence of loads (overloads) of individual groups or specimens;

\[ \eta_4 = 3.0 \] – takes into account the range of fatigue characteristics depending on the number of identical structures that have been tested.

In many real engineering structures, failure occurs after a relatively small number of load cycles, expressed in several thousand. At the same time inside the material the phenomena inherent in fatigue (emergence and development of cracks) can occur. Therefore, the destruction of the material at a relatively small number of loads \((10^2 - 10^5)\) is called low-cycle fatigue. This is a definite simplification, because for structural plastic materials with a number of cycles up to \(10^3 - 2 \cdot 10^4\), quasi-static failure can occur.

For the model the process of fatigue failure of the structure power elements of a specialized armored vehicle, the following algorithm must be followed:

- on the basis of the tactical and technical task to find out which roads are planned to operate a specialized armored vehicle. What percentage of the total mileage of the car will be the mileage on the roads with the worst micro-profile;

- on the basis of DSTU-P STANAG 4370: 2017 to determine the frequency and amplitude of vibration overload when driving a car on the road with a given microprofile at a given speed;

- using the calculation model of the power structure to calculate the mechanical stresses that occur under quasi-static loading with certain amplitudes, and to determine the critical places of the power structure where the maximum mechanical stresses occur;

- using a mathematical model of linear summation of damage to calculate the number of load cycles with a given amplitude, which leads to fatigue failure of the material;

- according to the road microprofile (according to DSTU-P STANAG 4370: 2017), the frequency of loads of this amplitude and speed to determine the mileage before the fatigue failure of the power elements of the structure of a specialized armored vehicle.

To determine the resource (mileage) of the vehicle in operation, it is necessary to set a certain margin for fatigue strength [1, 10]. This is due to the fact that the actual properties of the material are usually worse than those obtained in the laboratory on specially prepared samples. Deterioration of properties is influenced by the peculiarities of the fabrication of the material itself, technological features of the assembly of the power structure and the action of the environment. To determine the resource of the power structure by calculation, it is necessary to reduce at least three times the mileage before the fatigue failure of the power elements of the structure.

Since the load of the structure power elements of a specialized armored vehicle is stochastic, to implement the above algorithm requires simulation of the state of the structure [6].

The choice of methods for collecting and processing observational data mostly depends on what physical phenomenon is being studied and on achieved by the processing the goal. In general, there are the following main stages: data collection; registration; pre-treatment; assessment of basic properties; analysis; model construction; use of the model. Each of these stages requires a sequence of operations, which is shown in fig.9.
Data collection. When collecting data, primary measuring transducers are used, which convert energy from one form to another, which allows to perform an unambiguous quantitative assessment. This transformation generally requires 3 operations, as shown in fig.9. The number of operations depends on the physical size and design of the converter. A piezoelectric accelerometer is used to measure vibration overloads, which converts the acceleration into voltage.

Data registration. In most cases, there is a stage of data registration on media. Digital recording is currently used.

Data processing. The stage of data preparation for detailed analysis includes: editing – exclusion of abnormal signals, noise reduction, etc.; conversion from analog to digital form.

Evaluation of process properties. Determining the properties of the process is necessary for the correct choice of its further processing and analysis. The main properties of the process include: stationarity, periodicity, normality.

Analysis. At the stage of analysis, research is conducted on individual implementations of the process, the ensemble of implementations and the relationship between implementations. The analysis is performed in the time and frequency domain using common methods such as filtering, correlation analysis, spectral analysis. Modern digital technologies allow the use of methods that require appropriate computing power, such as sequence analysis, Kalman filtering, WaveLet analysis and others.

Build an object state model. When creating object models, the most common methods were the construction of simulation models: methods of constructing full-scale models; methods of construction of analog models; methods of constructing symbolic (mathematical) models. Computer simulation uses analog models and mathematical models.

At present, a characteristic trend in the field of research is the creation and use of automated computer systems. Examples of such complexes are the hardware-software complex of analysis and synthesis of modulated signals “Vector”, complex “PULSE”, complexes built on the basis of software environments Advanced Design System, MatLab, LabVIEW, HP IEE and others. Complexes built on the Microsoft Windows operating system using the NET FRAMEWORK platform are becoming more common.

On the basis of the developed concept, it is proposed to develop a typical method of checking the resource indicators declared by the manufacturer of the power elements of the car construction during the tests. It should contain the following components:

1. Documentation (with the necessary calculations of the strength and service life of the car) to be submitted for testing.

2. The main components of the hardware-software complex of measurements and data processing of vibration load.

3. The procedure for measuring the load of the power elements of the construction.
4. The order of processing and analysis of measurement results.
5. Algorithm for estimating the resource of power elements of the construction.

**Conclusions.**

The concept of conducting tests to determine the resource indicators of power elements of the construction of a specialized armored vehicle has been developed. Its typical design involves the presence of a steel frame that takes the load from the weight of the armor plates and transfers these loads to the car frame.

The main operational factor that determines the variable loads on the structure of a specialized armored vehicle is the microprofile of the road. In the preliminary (calculated) estimation of a resource of a power design of the car initial data, concerning action of a microprofile of the road on the car at its movement on various types of roads it is expedient to define taking into account VST 01.055.005-2021 – VST 01.055.013-2021.

The most modern method of calculating the stress-strain state of structural elements is the finite element method, which allows to perform simulation mathematical modeling of the structure under the action of various static and dynamic loads.

The use of the hypothesis of the linear rule of summation of damages at modeling of fatigue failure provides reliable definition of a resource of power elements of a design.

The use of a special anti-corrosion coating and ensuring constant control of its quality during operation significantly increases the resistance to fatigue.

When conducting tests for measurement, further analysis, modeling and forecasting of the resource of the power design of a specialized armored vehicle, it is expedient to create and use modern hardware and software measuring complexes.

**REFERENCES**

ОБГРУНТУВАННЯ КОНЦЕПЦІЇ ВИПРОБУВАНЬ ПО ВИЗНАЧЕННЮ РЕСУРСНИХ ПОКАЗНИКІВ СИЛОВИХ ЕЛЕМЕНТІВ СПЕЦІАЛІЗОВАНИХ БРОНЬОВАНИХ АВТОМОБІЛЕВ

В статті представлена концепція випробувань по визначенню і оцінці ресурсних показників силових елементів конструкції спеціалізованого броньованого автомобіля, типова конструкція якого передбачає наявність сталевого каркасу, що сприймає навантаження від ваги броньових листів, та передає ці навантаження на раму автомобіля. Концепція також передбачає приведення випробувань у відповідність зі стандартами держав-членів НАТО.

Встановлено, що основним експлуатаційним фактором, який визначає змінні навантаження на конструкцію спеціалізованого броньованого автомобіля, є мікропрофіль дороги. При попередній (розрахунковій) оцінці ресурсу силової конструкції автомобіля, є метод скінчених елементів, який дозволяє виконувати імітаційне математичне моделювання конструкції при дії статичних і динамічних навантажень.

При моделюванні втомного руйнування конструкції для більш достовірного визначення ресурсу автомобіля використовуються гіпотеза лінійного правила підсумовування пошкоджень.

При проведенні натурних випробувань пропонується використання сучасного апаратно-програмного комплексу для вимірювань фактичних характеристик навантаження автомобіля при русі дорогами різного типу.

Ключові слова: спеціалізований броньований автомобіль, силові елементи конструкції, моделювання, ресурс.