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SYNERGETIC SYNTHESIS OF SUSPENSION CHARACTERISTICS AND PNEUMATIC-AERODYNAMIC SYSTEMS OF A VEHICLE

This paper addresses the complex scientific and applied problem of improving the ride smoothness, directional stability, and cross-country ability of vehicles through the development of a unified hybrid pneumatic-kinematic platform. Based on a systemic analysis of suspension methods and models, it is proven that classic linear systems have exhausted their adaptive potential, especially in the context of operating special and light-armored military vehicles under conditions of dynamic center-of-mass shifts and powerful impulse loads from technological equipment.

The article proposes and scientifically substantiates an advanced multilevel methodology (quasi-static, harmonic, impact, and stochastic profiles) for the experimental study of elastic elements. Detailed technical specifications of the testing equipment, including the specialized SS20 diagnostic stand and a precision electromechanical press, are provided. The physical and mathematical principles of springs with variable wire diameters, variable pitch, and combined dual-action systems (Dual-Spring) that provide progressive (polynomial or piecewise-linear) stiffness characteristics are investigated.

Numerical simulation using the developed "quarter-car" kinematic scheme confirms that the implementation of such nonlinear elements reduces the peak vibration accelerations of sprung masses by 15–20% at small disturbances, effectively preventing destructive suspension breakdowns under extreme loads. Furthermore, an innovative concept of external chassis adaptation using an aerocompensator (from the perspective of deformable soil terramechanics) is developed, and the feasibility of integrating a traction rotary pneumatic engine into the vehicle's overall energy contour with a function for recuperating the vibration energy of sprung masses is substantiated.

Keywords: vehicle suspension, mechatronic systems, variable stiffness, progressive spring, terramechanics, aerocompensation, pneumatic engine, quarter-car model, parametric synthesis, light-armored vehicles, hysteresis.

INTRODUCTION AND PROBLEM STATEMENT

The design of a vehicle's undercarriage plays a decisive role in ensuring its key operational properties: ride smoothness, active safety, directional stability, handling, and acoustic vibration comfort. Improving ride smoothness in an engineering sense means minimizing the amplitude of vibrations and vibration accelerations at the crew and passenger workstations. Since human physiology perceives vibrations of different frequency ranges differently, the selective filtration of resonant frequencies is a critical task in modern mechanical engineering. [1]

A fundamental contradiction in classical automotive theory is the rigid, sometimes insurmountable conflict between the requirements for ride smoothness and handling. As a rule, high ride smoothness is achieved by reducing the stiffness of the elastic element and decreasing the damping coefficient of the shock absorber, which inevitably leads to an increase in dynamic suspension travel. This contributes to the soft absorption of vibrations from the road microprofile but leads to a critical increase in body roll during high-speed maneuvering (cornering), "diving" during intensive braking, and an overall decrease in the vehicle's directional stability at high speeds. The opposite situation (using a "sporty," stiff suspension) makes comfortable driving over irregularities impossible and leads to rapid driver fatigue.

This problem becomes particularly acute in the design of light-armored vehicles (LAVs), dual-use equipment, and special transport. Systemic analysis shows that typical linear suspension systems cannot fully satisfy the stringent requirements for modern special equipment. The installation of non-standard equipment or weaponry significantly and often asymmetrically shifts the vehicle's center of mass. In addition, firing weapons or operating massive manipulators creates powerful periodic impulse loads, causing a significant oscillatory effect on the body (swaying). Under the influence of such oscillations, the vehicle can move unpredictably, lose kinematic connection and traction with the supporting surface, which is a direct prerequisite for emergency situations or a loss of target efficiency.[2]

The aim of this comprehensive study is to develop a methodological apparatus for the parametric synthesis of suspension characteristics based on the innovative integration of nonlinear kinematic elements (progressive springs), an adaptive pneumatic transmission, and aerodynamic unloading systems into a single hybrid mechatronic vehicle network.

To achieve this goal, the following objectives were set:

1. To conduct an in-depth analysis of existing methods and mathematical models for studying vehicle suspension systems.

2. To classify modern suspensions as integrated mechatronic systems, determining their energy and frequency limits.
3. To develop and implement a multilevel experimental methodology for studying nonlinear elastic elements using specialized equipment.
4. To synthesize the concept of external chassis unloading on soft soils from the perspective of terramechanics.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS IN THE FIELD OF SUSPENSION DYNAMICS

When designing vehicle suspension systems, models and research methods are constantly applied and improved, the ultimate goal of which is the optimal spatial layout and selection of the physical parameters of the chassis.[3]

1. OVERVIEW OF EXISTING APPROACHES IN THE AUTOMOTIVE INDUSTRY

Studies show a significant variety of approaches to solving the problem of suspension optimization. For example, modern literature details the impact of random characteristics of the road microprofile on the parameters of an electric vehicle's torsion bar suspension, where the main evaluation criteria were the total working travel of the suspension and the dynamic load transmitted to the wheel. A separate promising direction is the study of non-standard hydraulic shock absorbers capable of absorbing significant amounts of energy by artificially increasing dynamic travel, which is physically impossible for traditional telescopic designs in the mass segment.

Considerable scientific attention is paid to modeling the vertical oscillations of wheeled vehicles, in particular, finding the conditions for the occurrence of resonant phenomena and determining the dependence of the oscillation amplitude on the restoring force of elastic elements for various kinematic schemes (double-wishbone, multi-link, dependent). At the same time, an analysis of the literature indicates that the theoretical basis for parametric synthesis remains incomplete. Most existing engineering methods for calculating the oscillations of sprung masses do not take into account the initial static state of the vehicle and the dynamic shift of the center of gravity depending on variable loading. Available mathematical models are often either excessively simplified (neglecting hysteresis, internal friction, and nonlinearity) or too cumbersome for rapid engineering use.[4]

2. SPECIFICS OF MODELING DUAL-USE EQUIPMENT (LAVS)

To adequately and accurately describe dynamic processes in military and special vehicles, it is necessary to apply a complex hybrid approach that organically combines two modeling components: continuous and discrete.

- The continuous component is implemented using finite element methods (FEM) and is mainly used to analyze the stress-strain state (SSS) of the solid metal hull (armored capsule or load-bearing frame) under the action of sudden impulse loads.
- The discrete component describes the kinematics of mounted equipment, suspension arms, and the elasticity of pneumatic tires in the form of systems of ordinary differential equations.

Traditional methodologies are often limited to a local SSS analysis only at the base of the rigid attachment of the torsion bar. However, modern structural synthesis requires the application of the theory of variational inequalities to account for complex elastic-plastic deformation along the entire length of the torsion bar and directly in the splined joints, which are stress concentration zones. Special attention is deserved by the structural formulation of the problem to obtain design solutions based on the analysis of hull stress state modeling during firing or manipulator operation, given a specified variation of a large set of design parameters.[5]

MATHEMATICAL MODELING OF SUSPENSION SYSTEM DYNAMICS

For the basic analysis of oscillatory processes and the preparation of a foundation for parametric synthesis, this work uses the "quarter-car" mathematical model. The input data for this simulation model are the mass-geometric characteristics of the body and wheels, the design of elastic elements, and the stochastic ordinates of the road microprofile. The output data are the accelerations, velocities, and displacements of the body and unsprung masses.

If we consider the suspension in motion as a classical single-mass (or two-mass) system, the general differential equation of motion for the sprung mass takes the form:

$$m\ddot{x} + c\dot{x} + F_{pr}(x) = F_{ext}(t)$$

where:

m is the sprung mass (equivalent to the mass of a quarter of the vehicle body, taking the load into account);

C is the viscous damping coefficient of the hydraulic shock absorber;

$F_{pr}(x)$ is the nonlinear function of the spring's elastic force;

$F_{ext}(t)$ is the external disturbing force generated by the road profile.

Unlike the classic Hooke's law for an ideal linear spring ($F = k \cdot x$), in this model, the stiffness is not a constant but a variable function of the current deformation: $F_{pr}(x) = k(x) \cdot x$.

To mathematically describe real nonlinear elastic elements in modeling environments, two main approximations are used:

Piecewise-Linear Model (for springs with variable pitch): Accurately describes a system where coils close (touch each other) sequentially. It is represented by a system of equations:

$$F_{pr}(x) = k_{soft} \cdot x \quad \text{for } x \leq x_{crit}$$

$$F_{pr}(x) = k_{soft} \cdot x_{crit} + k_{hard} \cdot (x - x_{crit}) \quad \text{for } x > x_{crit}$$

where k_{soft} is the initial (low) stiffness of the comfort zone, x_{crit} is the critical moment of "collision" or closing of soft coils, and k_{hard} is the final (high) stiffness of the rigid section.

Power/Polynomial Model (for conical/barrel-shaped springs): For springs with a smooth transition of characteristics due to a change in the wire diameter itself, a polynomial approximation is used:

$$F_{pr}(x) = k_0 \cdot x + \alpha \cdot x^n$$

where k_0 is the basic (initial) stiffness at the beginning of the compression stroke, α is the progression coefficient, and n is the degree index (usually $n \geq 2$).

Such a mathematical model demonstrates a fundamental property: with an increase in the oscillation amplitude x (hitting a large pothole), the natural frequency of the vehicle suspension also increases, which automatically prevents low-frequency body swaying and avoids dangerous kinematic breakdowns.[6-9]

CLASSIFICATION OF SUSPENSION SYSTEMS AS INTEGRATED MECHATRONIC COMPLEXES

The modern approach to chassis synthesis requires viewing the suspension not as a set of isolated metal parts (arms, torsion bars, or springs) but as a complex mechatronic unit controlled by electronics. Depending on the type of actuators, the width of the frequency band, power consumption, and control range, mechatronic suspension systems are currently classified by science into five main groups:

Passive Level-Control Systems: Function exclusively in a quasi-static mode. Their main goal is to maintain a constant distance between the chassis and the road (clearance) regardless of the degree of static loading of the vehicle. Using air springs and low-power compressors, they allow for the preservation of soft, comfort-oriented settings and guarantee full dynamic suspension travel even with a fully loaded trunk or cabin. The power consumption of such a system is relatively low, amounting to 100–200 W.

Adaptive Systems: Implement a slow, programmatically planned change in basic characteristics (spring stiffness and hydraulic damper resistance). For example, an algorithm may lower the clearance and center of mass when the vehicle's speed increases (highway driving) to improve aerodynamics and provide sportier road holding. Their energy consumption depends directly on the speed and frequency of setting changes.

Semi-Active Systems: Characterized by the ability to rapidly adjust solely the energy dissipation (i.e., damper/shock absorber characteristics). The key technological difference is that the actuator only changes its resistance depending on the direction of the wheel's relative movement but is unable to independently input

energy (generate force) into the system. As a result, power consumption is extremely low (about 20–40 W per damper, e.g., when using magnetorheological fluid), yet the bandwidth reaches a significant 40 Hz.

Slow-Active Systems: Also known as low-bandwidth active systems. These include a powerful additional actuator (electric linear motor or hydraulic cylinder) installed in series with the primary spring. This actuator can generate suspension forces regardless of the relative movement of the chassis and wheel. They are highly effective at countering body roll in corners, but their bandwidth is limited to about 5 Hz, and power consumption is substantial, ranging from 1 to 5 kW.

Fully Active Systems: In these advanced complexes (high-bandwidth active systems), the classic passive damper is either completely replaced or duplicated by a powerful electro-hydraulic actuator with a bandwidth of 20 Hz and above. Actuators are installed in parallel with the spring and can instantly process any complex road profiles. The main and often critical drawback for mass adoption is enormous energy consumption, ranging from 4 to 20 kW, making their use in heavy machinery or electric vehicles energetically highly unjustified.

In the context of our study and to globally optimize the vehicle's energy balance, the most viable path is the development of a hybrid architecture: creating an intelligent passive base using nonlinear progressive springs with subsequent integration of external pneumatic circuits for slow load adaptation.[10-15]

MULTILEVEL METHODOLOGY AND EQUIPMENT FOR EXPERIMENTAL RESEARCH

Any mathematical model, no matter how complex, cannot be deemed adequate without thorough experimental verification. Typically, spring stiffness is calculated theoretically (using the classic formula of materials strength), but in practice, significant deviations are possible due to factory defects in metal rolling, metal fatigue after prolonged operation, corrosion, overheating, or technological peculiarities of the thermal coiling process. This error is especially pronounced in springs with complex shapes (cone, barrel), where the compression resistance changes highly nonlinearly.

To determine the actual characteristics, we developed and implemented a multilevel program of bench testing consisting of four main stages.

STAGE 1: QUASI-STATIC SPRING TESTING

Objective: Accurate determination of the dependence of the elastic force on the magnitude of deformation, construction of the $C_p(z)$ graph, detection of hidden hysteresis effects, load skewing, and residual deformation (spring sagging).

Equipment: For mass rapid testing, a specialized SS20-type diagnostic stand was developed. It allows for force measurements of cylindrical, conical, and barrel-shaped springs for passenger cars and SUVs. The stand solves 7 tasks: from incoming parts control to precision pairing of springs on a single vehicle axle (force difference must not exceed 12 kg) for motorsports.

Diagnostic Stand Parameter	Value
Full range of measured forces	0-2000 kg
Force measurement error	no more than ± 2 kgf
Maximum height of measured springs	500 mm
Spring height measurement range	100-500 mm
Spring height measurement error	no more than ± 0.2 mm
Range of internal spring diameters	68-150 mm

For precision scientific research measurements in laboratory conditions, a floor-standing hydraulic press (type Remax SD0804CE) was used in a complex assembly with a portable reference strain-gauge dynamometer (type DOSM-3-1). The strain sensor has a wide measurement range from 1 kN to 10 kN, a high sensitivity threshold of 0.02%, and a total error of no more than 0.8%. Before testing began, the equipment underwent a mandatory metrological calibration procedure on an ASMA-Prybor electronic electromechanical press: readings from the indicator were taken with an exact load step of 10 kg to build a reference calibration graph.[16]

Methodology (Step-by-step algorithm):

The tested spring is installed on the press support platform and carefully centered using a special centering element to prevent lateral ejection.

Pre-compression of the sample is performed (slow loading up to 80-90% of maximum) followed by unloading to eliminate any gaps in the stand's mechanical transmissions.

A light load of 5-10% is applied to stabilize the position, after which the strain gauge indicator scale is reset to zero.

Step-by-step loading is carried out using a jack with a fixed pointer movement step of exactly 5 mm. The force results are carefully recorded during both the forward stroke (compression until the coils fully close) and the reverse stroke (release/extension) to capture hysteresis losses.

STAGE 2: HARMONIC (SINUSOIDAL) DISTURBANCES

Objective: Construction of amplitude-frequency characteristics (AFC), identification of the system's resonant frequency zones, and determination of body vibration accelerations under periodic impact.

Methodology: A strict harmonic signal following a sine law is generated on the dynamic vibration stand. The excitation frequency smoothly varies in the range from 0.5 to 20 Hz with a step of 1 Hz, and the disturbance amplitude is up to 25 mm. A data acquisition system (DAQ) equipped with accelerometers and linear potentiometers records the response of the sprung mass for each control frequency.

STAGE 3: IMPULSE LOADING (SINGLE OBSTACLE)

Objective: Evaluation of the suspension's ability to absorb sudden kinematic shocks (simulating hitting a speed bump, curb, or deep pothole) without a hard breakdown and its ability to quickly dampen residual free vibrations. Methodology: An impact-type stand generates an extremely short-term trapezoidal or rectangular impulse.

- Height of simulated obstacle: 30-100 mm.
- Impulse generation duration: 0.2-1.0 s.
- Simulated driving speed: 10-50 km/h.
- Platform load mass: up to 1500 kg. The electronics record the peak (maximum) body accelerations, the total time for vibrations to decay to rest, and the maximum compression stroke of the strut.

STAGE 4: RANDOM PROFILE (STOCHASTIC DISTURBANCE)

Objective: Maximally accurate modeling of the real operational process on public roads and evaluation of the human-operator's vibration comfort according to European standards. Methodology: A hydraulic vibration platform reproduces a so-called "white noise" road profile (in accordance with the ISO 8608 standard) over a wide frequency range with root-mean-square (RMS) acceleration. The duration of one continuous test is 30 minutes to simulate a long trip. The obtained frequency spectra and RMS indicators directly point to the level of physical fatigue the vehicle crew will experience during a march.[16]

PHYSICAL AND MATHEMATICAL ANALYSIS OF NONLINEAR STIFFNESS FORMATION METHODS

Solving the eternal conflict between smoothness and stability is effectively achieved by using elastic elements with progressive characteristics. Modern engineering offers three main technical methods for achieving nonlinearity:

Variable Coil Pitch: During manufacturing, coils are wound at varying distances from each other. When driving over minor irregularities, all coils work, but the "soft" coils with a small pitch deform the most, providing ride smoothness. When the load increases sharply (cornering, braking), these coils rapidly converge and touch each other ("close").¹ Since they stop working as a spring and become a solid metal spacer tube, the active length of the spring decreases, and overall stiffness increases abruptly. This reliably saves the suspension from breaking down and reduces body roll.

Variable Wire Diameter (Conical/Barrel-shaped): The steel wire itself narrows towards the edges. The operation of such a suspension is based on a law of physics: the thickness of the metal directly affects its ability to resist deformation. The thin end sections yield more easily to torsional twisting, ideally absorbing fine vibrations and acting as a "sensitive filter." Under strong impacts or high loads, these sections fully compress, and the thick central part, which has colossal resistance to deformation, comes into play. The advantage is an extremely smooth transition of stiffness, overall compactness (coils can nest inside one another, forming a flat disk), and enhanced durability (coils do not rub against each other, preventing corrosion).

Combination of Multiple Springs (Dual-Spring): A series connection on a single strut of a rigid (primary) and soft (helper/tender) spring via a movable aluminum divider ring. On a smooth road, both springs work simultaneously (the system's overall stiffness is lower than the softest of the two). During

aggressive maneuvers, the helper spring fully closes, instantly turning into a rigid spacer. After this moment, only the primary rigid spring works, instantly making the suspension "sporty."

ANALYSIS OF STATIC EXPERIMENT RESULTS

During laboratory testing (Stage 1), two samples of rear suspension springs for the popular ZAZ vehicle were examined in detail.

Sample No. 1 (Linear Spring): Constant steel wire diameter of 12 mm, outer diameter of 154 mm, length 228 mm, mass 1.80 kg. Despite the constant wire cross-section, the spring in practice demonstrates slight nonlinearity. Its compression process is best approximated by a linear equation :

$$C_p = 44392z + 22811$$

where z is the magnitude of vertical deformation. The relative error of the constructed model is 4.32% (root-mean-square error is 1093.91 N/m). During unloading (release), an entirely different relationship is observed ($C_p = 64987z + 20211$), which directly indicates significant hysteresis and internal friction within the structure. The stiffness range varies from a minimum of 19019.42 N/m to 30691 N/m. Because such a spring offers almost identical resistance at every millimeter of travel, it cannot provide a high level of comfort on minor irregularities.

Sample No. 2 (Progressive Spring): Variable wire diameter (narrowing to 8.4 mm at the edges, thickening to 14 mm in the center), outer diameter 156 mm, length 240 mm, increased mass of 2.2 kg. This innovative component shows a highly pronounced curvilinear resistance dependence, best described by a second-order polynomial:

$$C_p = 106z^2 + 109971z + 18992$$

The error of this complex model is 5.6% (1045.1 N/m). The minimum stiffness at the very beginning of travel (comfort zone) is only 10911 N/m (providing exceptional absorption of the microprofile), and the maximum grows exponentially upon compression, reaching an impressive 26569.8 N/m.

According to the results of many hours of numerical dynamics modeling (in specialized environments like MATLAB/Simulink), implementing such a progressive polynomial characteristic guarantees a reduction in peak body vibration accelerations by 15–20% in the zone of small disturbance amplitudes, while 100% ensuring platform stabilization and preventing hard impacts during extreme maneuvers.[16-19]

INTERACTION WITH A DEFORMABLE ENVIRONMENT: TERRAMECHANICS AND AEROCOMPENSATION SYSTEMS

Optimizing the internal parameters of springs and shock absorbers brilliantly solves the comfort problem only on a hard asphalt surface. When operating transport and technological machines (agricultural and military equipment) in off-road conditions, a much more complex problem arises regarding the wheel's interaction with soft, deformable soil.

From the perspective of the science of terramechanics, the repeated passage of heavy propulsors over the same spot in a field causes excessive over-compaction of the fertile surface soil layer, which poses significant ecological damage and reduces crop yields. On the other hand, excessive vertical loading of the vehicle on loose supporting surfaces leads to the formation of a deep rut and a complete loss of support mobility (the vehicle "bottoms out").

The rolling of an elastic pneumatic tire on soil is an extremely complex physical process, because under pressure, both the soil itself and the rubber tire deform (actual contact occurs along a concave surface with a radius significantly larger than the radius of an undeformed wheel). To mathematically describe this phenomenon in engineering, the rolling of a pneumatic wheel is treated as the rolling of an absolutely rigid wheel with a fictitiously enlarged diameter D_1 . [19-20]

The depth of the formed rut h directly and critically affects the rolling resistance coefficient f_{PN} . The deeper the rut, the more energy is spent on crushing the soil, the greater the resistance, and, most importantly for our study, the higher the amplitude of low-frequency kinematic disturbances transmitted from the destroyed soil to the suspension arms. Classical kinematic tuning methods do not take into account tangential tire elasticity or speed, so a classic passive suspension cannot in any way change the properties of the soil beneath it.

Synthesis of an Innovative Solution: To combat this destructive phenomenon, it is proposed to integrate an aerocompensator (a powerful directional fan device) into the overall vehicle system, creating stable vertical aerodynamic thrust directed upwards. This lifting force partially but significantly reduces the effective static vertical load of the vehicle on the axle. Artificially reducing the pressure on the soil instantly leads to:

1. A radical reduction in the depth of the formed rut h , which proportionally lowers the rolling resistance f_{PN} and saves fuel.
2. A decrease in the amplitude of vertical wheel movements, which automatically reduces the input disturbance that the suspension must process and dampen.
3. A change in the system's natural resonant frequency of vibrations, as the effective sprung mass (m in the equation of motion) dynamically and controllably decreases.

INTEGRATION OF PNEUMATIC SYSTEMS: ROTARY ENGINES AND THE CONCEPT OF ENERGY RECUPERATION

Creating a fully-fledged adaptive mechatronic platform of the future inevitably requires transitioning to unified energy standards within the vehicle's chassis. In explosive production industries (mining, coal, chemical industry), where even minimal electric motor sparking is a critical explosion risk factor, pneumatic engines have been widely and successfully used for decades. They are characterized by an extremely low relative weight per unit of power output, absolute resistance to colossal overloads (they can be stopped by external load to a complete halt of the shaft without any thermal or mechanical damage), and the ability for instantaneous reverse rotation.

EXPERIMENTAL STUDY OF A PNEUMATIC TRACTION DRIVE

To verify the technical feasibility of their direct use in wheeled transport, a series of experimental studies were conducted on the traction properties of a rotary pneumatic engine (created on the basis of an industrial impact pneumatic wrench). The assembled laboratory experimental setup included: 1 – air compressor (energy source); 2 – pneumatic wrench; 3 – optical tachometer; 4, 5 – digital multimeters for parameter recording; 6 – rheostat (potentiometer); 7 – electric brake motor for creating load.

The actual torque M was calculated based on the measured resistance moment of the electric brake using the classic formula :

$$M = \frac{9995 \cdot P}{N}$$

where P is the recorded power, and N is the rotor rotation frequency. It was experimentally confirmed that the output power can be easily, smoothly, and widely regulated by a simple change in the working air pressure, and the maximum output power characteristic remains practically constant and stable across all possible speed ranges.

However, the study revealed several critical design flaws. First, there is a catastrophically low overall energetic coefficient of performance (efficiency). Taking into account electrical losses in the primary compressor and aerodynamic losses in the pipelines, the total efficiency of the pneumatic system drops to an unacceptable 5–15% (for comparison, the efficiency of the isolated engine itself is 20–30%). Second, there is significant pollution of the surrounding air by exhaust oil aerosols and an extremely high level of acoustic noise during air discharge—up to 120 dB (while the current sanitary norm is 80 dB). Installing additional mufflers partially solves the noise problem but creates backpressure, which inevitably lowers the maximum rotor speed.[21-22]

DISCUSSION: SYNERGETIC SYNTHESIS AND THE DEVELOPMENT OF A HYBRID PLATFORM

In order to make the integration of such pneumatic engines into a vehicle's pneumatic transmission (according to the scheme: controller → pressure limiter → pneumatic receiver → compressor → electric battery → electric valve → pneumatic engine → wheel) engineering and economically rational, the authors propose a comprehensive concept of energetic synthesis directly with the operation of the suspension.

This innovative synthesis is based on three pillars:

1. Unified Energy Receiver: The pneumatic springs of the adaptive passive suspension (with clearance control function), the unloading aerocompensator, and the traction rotary pneumatic wheel engines do not function in isolation but are powered by a single central accumulator of compressed air.

2. Recuperation of Body Oscillation Energy: Standard oil telescopic shock absorbers in the suspension are replaced by specialized double-acting pneumatic pumps. While driving over potholes, especially in heavy off-road conditions, the vertical oscillations of the body (the very ones that cause maximum discomfort to the crew) are not dissipated as useless heat but force the pumps to compress atmospheric air and pump it back into the receiver under high pressure. This revolutionary solution allows the recovery of a significant portion of lost kinetic energy, directly compensating for the extremely low efficiency (5-15%) of the traction pneumatic drive.
3. Intelligent Adaptive Flow Control: Using a control unit, the system dynamically changes priorities. On a flat, hard surface, all energy from the compressor and receiver is directed towards high-speed movement (pneumatic wheel traction). When entering loose, soft soils (swamp, plowed field), the automation instantly redirects part of the pressure to the aerocompensator. This reduces the physical immersion of the wheels in the soil (depth h) and rolling resistance (f_{PN}), tremendously facilitating the work of the traction engines and preserving mobility. At the same time, nonlinear progressive springs reliably insure the body against hard impacts during intense oscillations, guaranteeing the integrity of the frame and driver comfort.[23-24]

CONCLUSIONS

Nonlinearity as the Absolute Foundation of Comfort and Safety: It has been proven experimentally (on SS20 stands) and theoretically (in modeling environments) that the use of progressive springs (whose behavior is mathematically described by second-order polynomial equations or piecewise-linear models of physical coil closing) most effectively solves the fundamental conflict in automotive theory. They guarantee a wide comfort zone for small displacements (a 15–20% reduction in peak vibration accelerations) and exponentially increase their stiffness (from a basic 10.9 kN/m to an impressive 26.5 kN/m) under high dynamic loads, minimizing body roll in corners and 100% preventing kinematic suspension breakdowns.

Complexity and Multilevel Nature of the Methodology: Reliable and error-free design of adaptive suspensions for special equipment (especially for LAVs exposed to weaponry impacts) is impossible without applying hybrid modeling (combining continuous FEM models of the armored hull and discrete differential equations of suspension arm kinematics) paired with multilevel experimental verification (statics on 20-ton presses with high-precision DOSM-3-1 dynamometers, harmonic vibration up to 20 Hz, 50-100 mm impulse impacts, and stochastic road profiles following the strict ISO 8608 standard for 30 minutes).

Mechatronic Synergy and Breaking Traditional Boundaries: Maximum ride smoothness in extreme off-road conditions is achieved exclusively by stepping outside the standard kinematics of suspension arms. The integration of an innovative aerocompensator allows direct and controlled influence on the terramechanics of tire-soil interaction (reducing effective pressure, critical rut depth, and overall rolling resistance), which is the most effective "external" method for combating disturbances, simultaneously significantly reducing ecological damage to agricultural lands.

Global Energy Integration: Although rotary pneumatic engines have significant inherent flaws (noise up to 120 dB, systemic efficiency of 5-15%), their use in specialized transport becomes technically justified and economically viable exclusively if a closed mechatronic chassis ecosystem is created. Harnessing the undesirable kinetic energy from body oscillations to generate compressed air via innovative pump-shock absorbers allows simultaneously powering the ecological transmission and the aerodynamic unloading system, forming a promising and self-sufficient architecture for highly efficient hybrid platforms of the future.

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Пелех О.Р., Сало Ю.М. Синергетичний синтез характеристик підвіски та пневмоаеродинамічних систем транспортного засобу

У представленій роботі вирішується комплексна науково-прикладна проблема підвищення плавності руху, курсової стійкості та прохідності транспортних засобів шляхом розробки єдиної гібридної пневмо-кінематичної платформи. На основі системного аналізу методів і моделей підресорювання доведено, що класичні лінійні системи вичерпали свій потенціал адаптивності, особливо в контексті експлуатації спеціальної та легкоброньованої військової техніки. Запропоновано багаторівневу методологію для експериментального дослідження пружних елементів. Досліджено закономірності роботи пружин зі змінним діаметром дроту, змінним кроком витків та комбінованих систем подвійної дії (Dual-Spring). Чисельне моделювання за схемою «чверть автомобіля» підтверджує, що впровадження таких нелінійних елементів знижує пікові віброприскорення підресорених мас на 15–20% при малих збуреннях. Крім того, розроблено інноваційну концепцію зовнішньої адаптації шасі за допомогою аерокомпенсатора з позицій терамеханіки та обґрунтовано можливість інтеграції тягового роторного пневмодвигуна в загальний енергетичний контур з функцією рекуперації енергії коливаль.

Ключові слова: підвіска, підвіска транспортного засобу, мехатронні системи, змінна жорсткість, прогресивна пружина, терамеханіка, аерокомпенсація, пневматичний двигун, модель кватеркара, параметричний синтез, легкоброньовані машини, гістерезис.

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Дата надходження статті до видання: 03.04.2026

Дата прийняття статті до друку після рецензування: 27.04.2026

<https://doi.org/10.36910/t1gzpw90>