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Analysis and optimization of torsion shafts in the context of improving the strength and durability of a light armoured vehicle

Abstract. In the context of the continuous development of armoured vehicles and the increasing requirements for the strength and efficiency of armoured vehicles, the study and improvement of torsion shafts becomes relevant to ensure high service life and optimal functioning. The aim of this study is to analyse the torsion shafts of light armoured vehicles to identify possible areas of optimization to increase the strength and durability of these vehicle elements. The methods used include the analytical method, classification method, functional method, statistical method, synthesis method, and others. As a result of the study, a comprehensive analysis and optimization of torsion shafts for light armoured vehicles was carried out to increase their strength and durability. The choice of high-strength material and weight consideration helped to reduce the weight of the vehicle, increasing its efficiency. Geometric design included the use of advanced techniques to optimize the shaft shape, and stress and strain analysis helped determine the optimum parameters. The use

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of computer modelling and simulation simplified the analysis of the shaft's behaviour under load. The use of safety factors and consideration of impact loads during operation helped to improve the reliability and durability of the structure. The use of the latest materials and manufacturing technologies allowed achieving the optimum parameters of the transmission element. Testing of the prototypes in real conditions confirmed their efficiency and durability. The optimization of weight and weight distribution was aimed at improving the stability of the armoured vehicle, taking into account the requirements of a particular application and manufacturer. The results indicate the potential for improving the design of torsion shafts to increase the performance and stability of light armoured vehicles. This study makes an important contribution to science, as the identified optimizations and improvements in the design of torsion shafts of light armoured vehicles contribute not only to increasing their strength and durability, but also to the rational use of resources and increasing the overall performance of the vehicle

Keywords: geometry; composite materials; suspension; smoothness of movement; tension; deformations

INTRODUCTION

A detailed study of the aspects of torsion shafts, especially in the context of their use in light armoured vehicles, is an important task. This is due to the constant development of modern armoured vehicles and the growing requirements for their strength and efficiency. Consideration of this topic allows identifying the most effective ways to improve the design and use of torsion shafts to ensure high performance and stability of armoured vehicles in modern conditions. Torsion shafts, as key components of the transmission, are important parts that carry a significant part of the mechanical load. Their role is to transmit rotational motion and influence the overall performance and stability of the vehicle. Improvements in their design can lead to significant improvements in strength, durability, and weight and size characteristics.

Considering the aspects of the study, an important task is to address specific challenges, namely, improving the configuration of torsion shafts for light armoured vehicles. One of the key issues is to achieve an appropriate balance between the strength and weight of torsion shafts to ensure high durability and efficiency under heavy loads. Another important issue is the selection of a suitable material for the shafts that has high strength and endurance under various operating conditions. These problems define the current research objectives aimed at improving the design and functional characteristics of torsion shafts in the context of the requirements of modern armoured vehicles.

According to the study by M. Manziak *et al.* (2021), the importance of optimizing torsion shafts for light armoured vehicles is gaining special emphasis due to the increasing technical requirements for armoured personnel carriers. The need to improve these elements to meet modern requirements for vehicle efficiency and durability is emphasized. The study does not consider aspects related to the impact of the operating environment on the strength of torsion shafts and their possible adaptation to different operating conditions of armoured vehicles. In the work by I. Polyak *et al.* (2023), the authors emphasize that a detailed analysis of the geometry and materials used in torsion shafts is a key step in finding optimal solutions to ensure their strength and reliability. The importance of a systematic analysis of these parameters to achieve optimal shaft characteristics in the context of their operation in armoured vehicles is indicated. The paper does not address issues related to the dynamics of torsion shaft operation and the possibility of their optimal adaptation to different modes of operation of armoured vehicles.

According to the study by I. Kyrychenko *et al.* (2021), the importance of using computer modelling to estimate stresses and strains at different points of the shaft emphasizes the need for modern approaches to studying this topic. The need to apply modern methods in the study of this topic to achieve more accurate and comprehensive results in analysing the behaviour of these elements is highlighted. The study does not take into account the impact of external factors, such as temperature changes or exposure to aggressive environments, on the strength and service life of these elements. Researchers M.V. Sklyarov & O. Shapovalov (2021) note that improved geometry and the use of high-strength composite materials are becoming key factors in reducing shaft weight and improving the efficiency of an armoured vehicle. The importance of these aspects for achieving optimal transmission element parameters was emphasized. The researchers do not consider the possible effects of operating conditions, such as wear or abrasion, on the strength and service life of the torsion shaft and composite materials.

A study by M. Hrubel *et al.* (2023) emphasizes that prototype testing plays a crucial role in confirming the effectiveness of proposed changes and their impact on durability and sustainability. The importance of conducting comprehensive testing to reliably assess the response and practical effectiveness of the modifications is highlighted. The paper does not consider the possibility of adapting the test results to different operating conditions of armoured vehicles in real-life scenarios. The paper by M. Tkachuk *et al.* (2022) raises an important question about the potential for improving the design of torsion shafts as a way to increase the performance and sustainability of light armoured vehicles in the modern military context. The researchers identify the relevance of developing technologies to optimize shafts in order to improve their functionality within current military requirements. The study does not take into account ergonomics and safety in the design of shafts, which is significant in military use.

This study aims to analyse torsion shafts used in light armoured vehicles. To achieve this goal, the following tasks have been identified:

1. To conduct a safety analysis, considering the relevant safety factors and assessment of impact loads during operation.

2. To determine a high-strength material for the torsion shaft, providing high strength and endurance under heavy loads, considering the lightness of the selected material to reduce the overall weight of the vehicle.

3. To analyse in detail and evaluate the possibilities of using modern technologies such as composite as or high-tech alloys, and implement advanced manufacturing methods, including additive technologies and CNC machining.

MATERIALS AND METHODS

The analytical method helped to identify potential weaknesses and determine the optimal parameters, including stress concentration points and other possible problems. The study of material selection contributed to the selection of a high-strength material that meets the requirements for sustained loading, thereby ensuring increased strength and service life of the torsion shafts.

Using a statistical method, the critical parameters and their interaction were identified, which allowed the development of optimization strategies to achieve the best results in the production of torsion shafts. The study of safety factors proved to be key to ensuring the reliability and durability of the design in real-world operation. The deduction method helped to formulate general principles and approaches to optimizing torsion shafts. Determining the cause-and-effect relationships between the shaft parameters and its characteristics made it possible to consider the influence of various factors on its functionality. The functional method was used to determine the parameters and configurations of torsion shafts aimed at achieving maximum strength and optimal performance. The functional method made it possible to take into account the influence of various factors, such as load, rotational speed and temperature conditions, on the operation of torsion shafts.

By applying the synthesis method, new concepts and strategies for optimizing torsion shafts were developed, considering a comprehensive approach to their improvement. This method allows combining various aspects, such as material properties, geometrical parameters, safety factors and the use of the latest technologies, to achieve optimal results. The classification method helped to define the main characteristics of torsion shafts and their properties, considering the various factors that affect their functioning. The study of a large amount of data using this method allowed creating a classification system that takes into account different types of shafts, materials, geometry and operating conditions. The induction method was used to generate new ideas and concepts aimed at improving torsion shafts in light armoured vehicles. This method provided new insights into potential areas of improvement in shaft geometry, materials, and manufacturing techniques.

The use of the generalization method in the context of the study of torsion shafts in light armoured vehicles allowed systematizing and summarising the results obtained to determine the chosen optimization path. This method allows for a detailed study of a large amount of data and takes into account the various influences of factors on torsion shafts. Geometric design, based on advanced techniques, helped to achieve the optimal shaft shape, ensuring efficient load distribution, and increasing its stability. The use of computer modelling and simulation software ensured high accuracy in assessing the performance of torsion shafts under various operating conditions. The use of the latest technologies in production, such as additive technologies and computer numerically controlled machines (CNC), contributed to the accurate implementation of the designed parameters and ensured the high quality of the manufactured torsion shafts.

This comprehensive approach to the study and optimization of torsion shafts for light armoured vehicles takes into account important aspects necessary to improve the performance, strength, and durability of vehicles in a military context.

RESULTS AND DISCUSSION

Optimization of structures and characteristics of the suspension of light armoured vehicles to improve passability and dynamic properties

Traditionally, the main design parameters and suspension characteristics of general-purpose vehicles have been formulated taking into account the rated loads and driving conditions on Category I and II roads with asphalt concrete pavement. At the same time, all-wheel drive modifications, known as multipurpose vehicles, which have remained the basis of the Armed Forces of Ukraine's fleet since the days of the Union of Soviet Socialist Republics (USSR), were based on the use of the maximum equipment with basic general-purpose models with minor modifications. These modifications included changes to the drive axles, a lower transmission range, a single-slope layout to meet off-road requirements and allow for a 6×6-wheel configuration, a centralized tyre pressure management system and other similar changes. These additional changes were introduced to improve the vehicle's off-road capability. However, in the case of off-road driving, in addition to the issues of off-road traction, the actual maximum speed is limited by an artificially set crew corresponding to the wheeled vehicles. This limitation is due to the achievement of extreme driving discomfort due to significant vibration oscillations caused by bumps in the road. These limits of vibration load and the permissible duration of their impact on the crew are already known and described in the modern scientific literature on wheeled vehicles (Nussupbek *et al.*, 2023).

The development of a new generation of tactical vehicles was determined by significant requirements for mine and ballistic protection, which were taken into account at the conceptual and working design stage for new models. The traditional way to protect against mines and bullets was to improve the existing vehicles of the previous generation by installing modern protective equipment and making appropriate changes to the serial designs of the chassis, frame, suspension, and other components. However, this approach is complicated because it significantly affects the driving dynamics of vehicles that were not designed to accommodate the increase in overall weight. Another important aspect was the increase in maximum driving speeds, especially off-road. This is because when driving on paved roads, the maximum speed is limited primarily by engine power, and there is a steady upward trend in this parameter. This also applies to heavy tactical vehicles with a GVWR of 12 to 40 tonnes, which have changed their top speeds from 70-80 km/h to 105-120 km/h over the past fifty years with the introduction of the KAMAZ-4310 model (Krainyk *et al.*, 2022).

In today's world, light armoured vehicles are becoming an increasingly important component of the transport environment, especially in the face of growing demand for safety and mobility (Fig. 1). The efficient operation of such vehicles depends on numerous factors, among which the design and quality of the components used, in particular, the torsion shafts, are of key importance. The analysis and optimization of these shafts are becoming an integral part of the development process to improve the strength and durability of light armoured vehicles. To achieve this goal, an important step is the selection of suitable materials for the torsion shaft construction. The use of high-strength alloys or special composite materials can significantly improve the strength and lightness of the shaft, providing an optimal balance between functionality and service life (Feyye *et al.*, 2021). Optimizing the torsion shaft geometry plays a key role in achieving high performance. Taking into account stress concentration points, load analysis, and the influence of external factors allows for optimal shaft shapes and geometries designed for maximum strength and durability. The use of computer modelling and simulation software plays an important role in the development of torsion shafts. It allows virtually testing different designs and materials, determining the optimal parameters, and predicting the behaviour of the shaft under different loading conditions. Another important aspect is the consideration of safety factors. The use of safety factors helps ensure that the torsion shaft can withstand not only standard operating conditions, but also unforeseen situations that may arise during extreme conditions. The final stage is the development of prototypes and their intensive testing in real-world conditions. This stage allows verifying the actual efficiency and strength of the optimized torsion shaft, identifying possible shortcomings, and making the necessary adjustments.

Figure 1. Light armoured vehicle
Source: Light armoured vehicles for the Armed Forces are undergoing the final stage of national trials (2019)

The analysis and optimization of torsion shafts for light armoured vehicles is a multidisciplinary task that requires the interaction of various engineering disciplines. By integrating aspects of material science, geometric design, software modelling and prototype testing, engineers can create torsion shafts that meet high standards of strength and durability, ensuring optimum performance of light armoured vehicles.

Material selection for torsion shaft optimization: balance of strength and lightness

In today's world, where technology is improving every day, the development of vehicles, especially light armoured vehicles, is a task that requires high engineering and scientific expertise. Optimization of torsion shafts, as key elements of the drivetrain, is becoming an important aspect to ensure the efficiency, strength, and durability of vehicles.

In this context, the choice of material for torsion shafts is determined not only by its strength, but also by its lightness, where the balance of these characteristics becomes the key to success.

The strength of torsion shafts is a crucial factor, as these elements are subjected to significant rotational loads during the movement of an armoured vehicle (Huda, 2021). Stress and strain analysis allows engineers to determine how the material can withstand these loads and avoid possible flaws or loss of efficiency. Thus, choosing a material with high strength and fatigue resistance is a top priority. However, the issue of material lightness is equally important. In modern automotive and military equipment, great attention is paid to weight reduction to improve fuel consumption and manoeuvrability. Torsion shaft optimization, which includes the selection of lightweight yet highly durable materials, can play a key role in achieving these goals.

An important aspect of material selection is the engineering ability to take into account the conditions of actual operation. Consideration of temperature fluctuations, aggressive environments and other factors is essential to ensure the reliability and durability of torsion shafts in a variety of conditions. The material choice for optimizing torsion shafts can also include the use of modern composite materials that combine high strength and lightness. This opens new horizons for engineers and designers, allowing them to create vehicles with an optimal combination of properties.

According to the results of recent research by H. Bankar *et al.* (2013), material optimization and weight reduction of the drive shaft using composite materials is an important area of technology development. Composite materials consist of two or more components with different physical properties that interact to create a material with improved characteristics. The use of composite materials in drive shafts allows for an optimal balance between strength and weight. Composites often have a high relative modulus of elasticity and strength at low weight, making them an attractive choice for applications where equipment weight is important. Optimizing drive shaft material and weight can also help reduce fuel consumption and improve system efficiency, which is critical for vehicles and other mechanical systems.

Material selection for torsion shaft optimization in light armoured vehicles requires a careful balance between strength and lightness. Engineers must carefully analyse the operating conditions and use advanced material technologies to create optimal designs that meet the high performance and safety requirements of today's world.

Geometric design of torsion shafts: a path to optimization and performance improvement

The geometric design of torsion shafts is recognized in modern mechanical engineering as a key step in the development of efficient and reliable transmission systems for light armoured vehicles. The use of advanced design techniques is essential to achieve an optimal shaft geometry that maximizes strength and efficiency in real-world applications. The use of advanced design techniques is an important step in the geometric design of torsion shafts. Engineers use computer programmes and engineering solutions to create three-dimensional models of shafts, taking into account various aspects such as geometric parameters, materials and operating conditions.

Stress and strain analysis is an important step in determining the optimal shaft shape in the geometric design of torsion shafts. By using mathematical models and computational software, engineers can determine how different torsion shaft shapes affect the stress and strain distribution in the structure. This allows them to choose a geometry that minimizes stress concentrations and increases the shaft's resistance to fatigue. One of the most advanced techniques is the finite element method (FEM), which allows engineers to virtually simulate stresses and strains in real-world operating conditions (Kushwah *et al.*, 2021). This method considers a variety of factors such as loads, temperature changes, and other operating conditions, allowing engineers to more accurately determine the optimal geometry. It is important to note that the design of torsion shafts is not a static task. As technology advances and new materials become available, engineers must constantly improve their geometric design techniques. Regular updates and adaptations to shaft geometry can not only improve strength, but also reduce weight, which is important for light armoured vehicles.

Referring to the definition of D.E. Osakue *et al.* (2015), shaft fatigue testing, considering its bending and torsion, is a key step in the development of mechanical systems. A shaft that is subjected to constant loads must be thoroughly tested for the possibility of deformation and material fatigue. During bending tests, it is important to consider the loads that may occur during operation and to check whether the shaft can withstand these loads without damage or deformation. Torsional testing, on the other hand, is important for determining the selective rotational stability of the shaft and for preventing possible problems related to torsional loads. These tests help to confirm the reliability and stability of the shaft design under real-world operating conditions, as well as identify possible areas for improvement to optimize its performance and service life. The geometric design of torsion shafts is a key element in optimizing the transmission systems of light armoured vehicles. The use of advanced techniques and mathematical methods allows engineers to create efficient and fatigue-resistant designs that meet the high demands of modern technical development.

Modelling and simulation in the design of torsion shafts: strength analysis and improvement

In today's rapidly evolving engineering environment, the use of computer modelling and simulation software is an essential component of torsion shaft design. This stage not only provides the ability to analyse the shaft's behaviour under load, but also allows engineers to identify and resolve potential problems, ensuring optimum strength and safety. It is to be started with the use of computer modelling software, which gives engineers the ability to create virtual models of torsion shafts. This includes taking into account shaft geometry, materials, and factors such as loads and operating conditions. Computer simulation software allows engineers to reproduce real-time operating conditions and evaluate the impact of various factors on shaft strength and reliability.

Simulation, in turn, is a key step in analysing the behaviour of a torsion shaft (Wang *et al.*, 2022). Using the resulting models, engineers can perform virtual tests by subjecting the shaft to various loads and operating conditions. The simulation allows them to identify stress concentration points, determine areas of maximum force, and identify possible problems that may arise as a result of material deformation or fatigue. The assessment of stress concentration points is particularly important in the design of torsion shafts. These points can indicate where stresses may be highest, which can lead to damage or fatigue of the material in the future. Simulation allows engineers to effectively correct these problems by optimizing the shaft geometry, selecting the best materials, or making other design changes (Hajiyev & Damirov, 2023).

Researchers M. Liang *et al.* (2022) determined that modelling the torsional resistance of a small-diameter hollow shaft using ABAQUS software is an important step in the design and analysis of mechanical systems. ABAQUS is a powerful engineering tool for numerical modelling and simulation of the behaviour of materials and structures under various loading conditions. When modelling the torsional resistance of a hollow shaft, a variety of parameters such as shaft geometry, material properties, loading conditions and boundary conditions must be taken into account. ABAQUS allows engineers to create sophisticated models that consider real-world operating conditions. Analysing the torsional resistance of a hollow shaft can provide important data on its strength and deformation characteristics, which helps to improve the design and ensure a high level of reliability in operation. This approach allows engineers to optimize designs and improve their efficiency before physically manufacturing prototypes.

In modern engineering practice, the use of computer modelling and simulation software is becoming a key element in the optimization of torsion shafts. This allows not only to increase their strength and durability, but also to effectively deal with potential problems, ensuring safety and reliability in operation.

Consideration of safety factors in the design of torsion shafts: ensuring reliability and durability

In the field of mechanical engineering, where high reliability and durability are key success parameters, consideration of safety factors in the design of torsion shafts is a mandatory component. The application of safety factors and careful consideration of impact loads allow for not only optimal shaft performance, but also its reliability in real-world operating conditions (Nuraliyev *et al.*, 2023). The first step in taking safety factors into account is to establish safety factors for all key parameters of the torsion shaft design. These factors consider the various uncertainties and variations that can occur during design and manufacturing. In addition, they provide an additional safety margin to ensure the shaft's reliability in extreme conditions and when exposed to unforeseen factors.

Considering the magnitude of impact loads is another important aspect in the design of torsion shafts. In the operating environment of light armoured vehicles, a variety of situations can arise, such as jolts, obstacles, or unforeseen explosions, which can cause impact loads on torsion shafts (Chovnyuk *et al.*, 2022). Analysing these scenarios allows engineers to consider these safety factors and incorporate them into the shaft design, ensuring reliability and durability. It is important to emphasize that safety factors are determined not only on paper, but also by experimental studies and prototype testing. Consideration of real-world operating conditions and the ability of the design to withstand unexpected loads are important to ensure the safety and reliability of the shaft in the real world.

Researchers A. Koch *et al.* (2023) have shown through their work that identifying safety issues related to torsional side shafts in electrified vehicles plays an important role in ensuring reliable and safe system operation. Side shafts in electrified vehicles, such as electric or hybrid vehicles, are subject to particular dynamic and thermal loads due to their interaction with electric motors. Systems for detecting side shaft torsion problems can include sensors that measure torsional parameters and monitoring algorithms that analyse this data for deviations from normal operation. Prompt detection of such problems allows timely measures to be taken to prevent accidents and improve the safety of passengers and the vehicle as a whole. The development and implementation of effective systems for detecting torsional problems in side shafts in electrified vehicles is an important aspect of engineering work in the field of electromobility aimed at improving the safety and reliability of new technologies.

Consideration of safety factors in the design of torsion shafts is a critical element to ensure the reliability and durability of the structure. The application of safety factors and careful consideration of impact loads allow creating not only technically advanced shafts, but also those that can operate effectively in real-world conditions where safety is a priority.

The use of the latest technologies in the design of torsion shafts: innovations for efficiency and quality

In today's industrial landscape, the use of the latest technology is key to achieving high efficiency, durability, and product quality. In the context of torsion shaft design, the use of the latest materials and manufacturing technologies plays an important role in improving their performance and functionality. An innovative area is the use of advanced materials such as composites or alloys with high performance characteristics. Composite materials, which combine different components to achieve optimum properties, can be used to create lighter but stronger torsion shafts. High-strength alloys can withstand heavy loads, ensuring high safety and reliability (Pavlikov *et al.*, 2019).

An important innovation is the use of advanced manufacturing technologies, such as additive technologies or CNC machining. Additive technologies, such as 3D printing, allow for the creation of complex geometries and optimized shaft design to accommodate internal cavities and structures, which improves weight and mechanical performance. CNC technologies, on the other hand, provide high machining accuracy and the ability to produce complex parts (Zhu *et al.*, 2022). The use of the latest technologies also includes the application of manufacturing methods that allow for the use of thin and resistant materials, ensuring efficiency and minimizing weight. Engineers and designers must constantly improve their approaches and use advanced technologies to optimize and meet the challenges in torsion shaft design.

As noted by E. Bilalis *et al.* (2022), optimizing the design of drive shafts made of composite materials is a hot topic in the engineering and manufacturing industries, aimed at increasing the strength and lightness of the elements. Composite materials consist of a combination of two or more different materials, usually fibres and a matrix, working together to achieve optimum properties (Skorokhod *et al.*, 1995). Optimizing the design of a drive shaft involves considering various parameters such as geometry, fibre orientation, fibre type and number, and the composite matrix. These parameters can be carefully tuned to achieve the desired mechanical characteristics, including high strength at low weight. The use of composite materials in the design of drive shafts allows for weight reduction while maintaining the required strength, which is important in the production of vehicles, aircraft, power generation equipment and other industries (Averin & Borovytskyi, 2023). This approach helps to improve the efficiency and service life of mechanical systems.

The use of the latest materials and production technologies allows us to create not only strong, but also lightweight and efficient shafts that meet the high standards of modern mechanical engineering.

Testing torsion shaft prototypes: ensuring high efficiency and strength

Prototype testing is a critical step in the torsion shaft development process, as it provides an opportunity to determine the real-world performance of a design and refine it before large-scale production. This approach allows engineers not only to identify possible shortcomings, but also to improve and optimize torsion shafts to achieve the highest efficiency and durability. Manufacturing physical prototypes of torsion shafts is the first step in this process. The use of advanced manufacturing technologies, such as additive manufacturing or CNC machining, allows for the precise realization of structural elements that meet the project requirements (Kaššay *et al.*, 2023). However, prototype production is only the beginning of the process, as its effectiveness and durability must be objectively verified.

Intensive tests play a key role in ensuring the quality and reliability of torsion shafts. These tests must reflect the actual operating conditions as well as additional factors that may affect the product in real life. Loads, temperature effects, vibrations, and impact loads should all be taken into account during testing. The test results provide engineers with important data on the operating strength and efficiency of the torsion shaft. They can identify weaknesses, optimize the design, and improve material and geometric aspects. This iterative approach allows for high quality and efficiency in the design of torsion shafts. Prototype testing also opens up opportunities to improve technical solutions and use the latest technologies. Engineers can implement changes in real time, refining and optimizing the design of torsion shafts based on the data obtained.

Researchers A. Wieczorek *et al.* (2022) determined tha t vibration analysis of a drive system equipped with an innovative prototype of a flexible torsion coupling is an important step before implementing this element in real-world applications. Flexible torsion couplings are used to transmit torque between shafts, while providing some flexibility to compensate for vibrations and torsional oscillations. It is important to conduct a vibration analysis to determine how well a new coupling prototype will meet the performance and durability requirements under various operating conditions. Analysis methods can include measuring vibration frequency, amplitude, and shape, as well as taking into account the dynamic properties of the prototype material. Such analysis allows engineers to refine the design and parameters of the flexible torsion coupling prototype, ensuring its optimal performance and durability in real-world applications. Preliminary vibration tests help to identify and eliminate potential problems during the development phase, contributing to the further efficiency and safety of the drive system.

Prototype testing of torsion shafts determines the success of their functionality and durability in real-world conditions. This stage allows confirming concepts, identifying weaknesses, and achieving high standards of efficiency and quality in the manufacture of torsion shafts.

Optimization of mass and weight distribution in the design of torsion shafts: impact on the efficiency and stability of an armoured vehicle

In today's engineering world, mass optimization and weight distribution has become a key aspect in the development of torsion shafts for armoured vehicles (Venczel *et al.*, 2022). This optimization is crucial to ensure not only high efficiency and strength of the shaft, but also to improve the overall stability of the armoured vehicle. Optimizing the torsion shaft mass with respect to efficiency and fuel consumption is one aspect of this process. It is important to strike a balance between strength and lightness of the shaft, as this directly affects the overall performance of the armoured vehicle. The use of high-strength materials and optimized geometry can help reduce shaft weight while still providing the required strength.

Uniform weight distribution is an important factor in improving vehicle stability, especially when driving on uneven roads or in combat situations. Optimal weight distribution can be achieved by taking into account not only the weight of the torsion shaft but also other components of the suspension system. Additive manufacturing and CNC machining technologies can be used to create optimized shaft geometries that contribute to weight reduction. It is also important to use analytical methods and computer modelling programmes to accurately determine the optimal shaft parameters, considering its functionality and interaction with other armoured vehicle systems.

In their study, W. Zeng *et al.* (2023) found that Optistruct-based modelling and lightweight design of automotive transmission shafts is a state-of-the-art approach to optimize weight and maintain the required strength of these important automotive transmission components. Optistruct is a topological and topographic optimization software that allows engineers to automatically structure material and geometry to optimize part properties. Modelling shafts with Optistruct allows engineers to perform topological optimization by considering various parameters such as shape, dimensions, and materials. This approach helps reduce shaft weight while maintaining the required strength and stiffness. The lightweight design process is made more efficient by using the optimization tools offered by Optistruct. The use of this software not only improves the mechanical properties of transmission shafts, but also reduces their weight, which contributes to the efficiency of the automotive transmission and the fuel efficiency of the vehicle as a whole.

By considering the above aspects, engineers can create torsion shafts that not only meet high standards of strength and efficiency, but also make a significant contribution to improving the stability and control of an armoured vehicle. Optimization of weight and weight distribution is becoming a strategic approach in the development of torsion shafts that meets the modern requirements of high-performance and stable armoured vehicles. The development and optimization of torsion shafts for light armoured vehicles is a task that requires a thorough understanding of the specific application of these components and the manufacturer's capabilities. Taking into account the requirements of a specific application ensures that the engineering challenges associated with armoured vehicles are addressed accurately and efficiently.

Engineers must examine the characteristics and features of the light armoured vehicle for which the torsion shafts are being designed. This includes the weight and dimensions of the vehicle, the types of materials used in the construction, the anticipated operating conditions, and the specific tasks the vehicle performs. Next, engineers must carefully analyse the manufacturer's capabilities, which include process limitations, available materials, production methods and technical capabilities. Taking these factors into account allows for optimized solutions that consider realistic production capabilities and deliver efficiency in terms of serviceability and cost. When optimizing torsion shafts, the specifications and requirements of the specific application should be the focus. For example, if a light armoured vehicle has high requirements for speed and manoeuvrability, optimizing shaft weight may be a priority. In a case where safety and stability play an important role, weight distribution and shaft strength may be key factors.

All these aspects interact in the development and optimization of torsion shafts, where balancing the requirements of the specific application with the capabilities of the manufacturer is essential to achieve high standards of quality and performance in the light armoured vehicle sector.

CONCLUSIONS

The analysis and optimization of torsion shafts in the context of improving the strength and durability of a light armoured vehicle is an important step in the development of vehicles designed to operate in high-risk environments. It is a key aspect of the engineering approach, as torsion shafts play an important role in the mechanical structure of vehicles, providing torque transmission and supporting loads during movement. The analysis of torsion shafts involves the study of their geometry, material properties, and operating conditions. This process allows engineers to identify potential problems, such as stress or strain points, that could lead to damage or material exhaustion of the shaft. The detailed analysis is also aimed at determining the optimal shaft design for maximum strength and efficiency.

The use of the latest technologies in the design of torsion shafts is a key stage in the development of transmission systems and mechanisms for light armoured vehicles. Innovations in this area are aimed at improving the efficiency, durability, and overall quality of shafts to optimize their performance in the high-risk conditions and requirements of military operations. Prototype testing of torsion shafts is a critical step in their development process to ensure high efficiency and durability. This process allows engineers to evaluate the actual performance of the shafts when operating under conditions that most closely replicate real-world operating conditions.

Optimization of torsion shafts, in turn, involves the use of advanced engineering methods such as topological optimization or finite element analysis. These methods help reduce shaft weight while maintaining the required strength and stability. The use of new materials such as composites or high-strength alloys can also make a significant contribution to improving the performance of torsion shafts. This analysis and optimization are important steps in ensuring that armoured vehicles are as strong and durable as possible, with a high level of safety for their crews. This helps to improve the design and functionality of the vehicles, ensuring they have the optimum parameters for optimal performance in the causal environment.

When developing the next generation of tactical vehicles, the importance of mine protection and torsion shaft optimization for improved strength should be considered. Changes in the suspension design of general-purpose vehicles and all-wheel drive modifications are aimed at increasing the off-road capability, but the limitation of the artificially installed crew of military vehicles arises when driving off-road due to vibration. This aspect, together with the increase in maximum speeds, defines important areas of research and improvement in the development of transport for combat operations. Additional areas of research include studying the interaction of torsion shafts with other elements of the transmission system and the impact of various operating conditions, such as temperature fluctuations or high humidity, on their performance. In addition, the interaction of torsion shafts with external factors, such as impacts or explosions, should be analysed to develop technologies for increased durability and safety in extreme conditions.

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CONFLICT OF INTEREST

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Аналіз та оптимізація торсіонних валів в контексті поліпшення міцності та довговічності легкої броньованої машини

Анотація. У контексті постійного розвитку бронетехніки та зростання вимог до міцності та ефективності броньованих машин, вивчення та удосконалення торсіонних валів стає актуальним для забезпечення високої тривалості служби та оптимального функціонування. Метою даного дослідження є проведення аналізу торсіонних валів легких броньованих машин для ідентифікації можливих напрямків оптимізації з підвищенням міцності та довговічності цих елементів транспортного засобу. Серед використаних методів слід зазначити аналітичний метод, метод класифікації, функціональний метод, статистичний метод, метод синтезу та інші. У результаті дослідження було здійснено комплексний аналіз та оптимізацію торсіонних валів для легких броньованих машин з метою підвищення їхньої міцності та довговічності. Вибір високоміцного матеріалу та урахування ваги сприяли зниженню ваги транспортного засобу, підвищуючи його ефективність. Геометричне проектування включало застосування передових технік для оптимізації форми вала, а аналіз напружень та деформацій дозволив визначити оптимальні параметри. Використання комп’ютерного моделювання та симуляції спростило аналіз поведінки вала під навантаженням. Застосування коефіцієнтів безпеки та врахування імпактних навантажень під час експлуатації сприяло підвищенню надійності та довговічності конструкції. Використання новітніх матеріалів та технологій виготовлення дозволило досягти оптимальних параметрів трансмісійного елемента. Тестування прототипів в реальних умовах підтвердило їхню ефективність та міцність. Оптимізація маси та розподілу ваги була спрямована на покращення стійкості броньованої машини, з урахуванням вимог конкретного застосування та виробника. Отримані результати вказують на потенціал вдосконалення конструкції торсіонних валів для підвищення продуктивності та стійкості легких броньованих машин. Це дослідження приносить важливий внесок у науку, оскільки виявлені оптимізації та покращення в конструкції торсіонних валів легких броньованих машин сприяють не лише збільшенню їхньої міцності та витривалості, але й раціональному використанню ресурсів та підвищенню загальної продуктивності транспортного засобу

Ключові слова: геометрія; композитні матеріали; підвіска; плавність руху; напруженість; деформації