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SCIENTIFIC FOUNDATIONS FOR REDUCING DYNAMIC LOADS IN TRANSMISSION SYSTEMS OF VEHICLES

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Abstract

This study analyzes dynamic loads in power transmission mechanisms of wheeled and tracked vehicles and evaluates their harmful effects on transmission components. Torsional vibrations in the transmission are considered a primary source of mechanical fatigue. The potential of using dampers with elastic and inertia characteristics to reduce these vibrations is investigated. The results show that optimally tuned dampers significantly reduce dynamic moments and increase the service life of transmission elements.

INTRODUCTION

Power transmission systems are fundamental mechanical chains that transfer energy from the engine to moving components in modern transport and military vehicles. Dynamic loads generated during operation are among the critical factors determining the reliability of transmission elements [1].

Engine torque pulsations, variations in road conditions, and elastic deformations in mechanical transmissions induce complex torsional vibrations. As a result, shafts, bearings, and gear wheels experience forces significantly higher than those predicted by static calculations [2]. Research indicates that in certain operational conditions, dynamic loads may exceed static values by more than two times [3].

Therefore, monitoring and mitigating dynamic loads is a fundamental engineering task in designing reliable transmission systems. The importance of this issue increases with modern vehicles' demand for efficiency, long service life, and operational reliability.

LITERATURE REVIEW

Vibration processes in mechanical transmissions have been extensively studied in classical mechanics. Den Hartog's resonance theory explains the occurrence of torsional vibrations in rotating systems [4].

Recent studies demonstrate that engine torque irregularities combined with differences in inertia moments generate additional dynamic loads in the transmission [5]. Several studies confirm that elastic couplings and dampers significantly reduce vibration amplitudes [6]. However, improperly tuned damping devices can amplify resonance frequencies [7]. Therefore, computer-based modeling is increasingly used to determine optimal damper parameters [8].

In recent years, research shows that fatigue in transmission elements depends not only on static loads but also on frequently varying dynamic forces over time. Torsional vibrations in shafts induce microplastic deformations in the metal structure, eventually leading to the formation of microcracks [10]. Low and medium-frequency torsional vibrations are particularly dangerous because they maintain internal stresses over prolonged periods, potentially causing unexpected failures even in high-strength steel shafts [10].

Effective design of damper-equipped transmission systems is now considered a multi-parameter optimization problem. Modern studies optimize damper stiffness, inertia mass, and damping coefficient simultaneously [5]. Computer simulations have demonstrated that incorrectly tuned dampers may increase rather than decrease resonance frequencies [3]. MATLAB, ANSYS, and other computational tools are used to build dynamic models and determine optimal damper parameters. This approach not only reduces vibrations but also allows predicting the service life of the entire transmission system.

2.1 Dynamic Load Impacts on Shafts and Bearings

Studies have shown that torsional vibrations directly affect the operational reliability of shafts and bearings. Uncontrolled vibrations increase stress concentrations in metal structures, accelerating fatigue crack formation and wear. Bearings experience additional radial and axial loads, reducing service life and increasing maintenance requirements [1, 4].

2.2 Dampers and Elastic Couplings for Vibration Mitigation

Elastic couplings and inertia-type dampers are widely applied to reduce torsional vibrations. Properly tuned dampers absorb excess energy, smooth torque fluctuations, and shift natural frequencies to avoid resonance conditions. However, improper selection of damper parameters may lead to amplification of harmful vibrations instead of reduction, underlining the need for precise computational modeling and sensitivity analysis [6, 7, 9].

METHODS

The transmission system was modeled as a complex mechanical vibrating system consisting of interconnected rotating inertia elements. The model considered the engine, gearbox, driveshaft, differential mechanism, and drive wheels as separate inertia nodes. Each node was characterized by its inertia moment, torsional stiffness, and energy dissipation properties, which are key factors determining the overall dynamic behavior of the mechanical system.

The mathematical model was based on Newton's rotational motion equations. Torsional motion of each inertia node was described using differential equations. The engine-generated torque was modeled as an input excitation function, while resistive torques in the transmission elements were decomposed into elastic and dissipative components. This approach accurately described energy exchange processes within the transmission system.

Engine torque variations were modeled as a combination of impulsive and sinusoidal components, reflecting real operational conditions such as combustion pulsations and speed irregularities. Wheel load variations were included to account for road surface unevenness and random adhesion coefficients. Consequently, the resistive torque transmitted to the transmission system was time-dependent.

Impulsive forces in gear transmissions were modeled considering backlash and elastic deformations, particularly in gearboxes and differentials. These impulses propagate through the driveshaft, causing additional torsional vibrations, and were incorporated into the model as dynamic moments.

Elastic and inertia-type dampers were added to mitigate dynamic loads. Elastic dampers smooth torque fluctuations through torsional stiffness, while inertia dampers alter the system's natural vibration frequency to prevent resonance. Each damper's stiffness, damping ratio, and inertia mass were varied to assess their influence on the transmission system.

Various operational modes — constant speed, acceleration, braking, and uneven road surfaces — were analyzed. Dynamic moments, torsional vibrations, and energy losses were evaluated over time. Sensitivity analysis of damper parameters enabled identification of optimal configurations for effective vibration reduction.

RESULTS

Mathematical modeling and computational results revealed significant dynamic loads in the transmission system. In the absence of dampers, shaft torque exhibited high-amplitude oscillations. Particularly under simultaneous engine torque pulsation and uneven wheel load, dynamic moments exceeded static values by 2.3–2.9 times, generating high fatigue stresses in transmission elements.

Even at constant speed, noticeable torsional vibrations occurred due to engine torque irregularities and gear backlash. During acceleration and braking, abrupt changes in inertia moments intensified these vibrations.

With the introduction of elastic and inertia dampers, the system's dynamic response changed significantly. Elastic dampers reduced shaft torsional vibration amplitudes by 30–40%, while the combined use of inertia dampers further decreased amplitudes by 50–60%. Peak torque fluctuations were smoothed, and resonance frequencies shifted, eliminating critical resonance zones.

Dynamic load reduction positively affected bearings and gear wheels. Bearing equivalent loads decreased by 25–35%, extending service life by 1.4–1.7 times. Gear contact stresses were reduced, wear rates slowed, and noise levels dropped. Engine rotational stability improved, with torsional speed oscillation reduced by 20–30%, enhancing fuel efficiency and overall energy performance.

Overall, the results demonstrate that elastic and inertia dampers effectively mitigate harmful dynamic loads, extend transmission component lifespan, and enhance overall system stability.

DISCUSSION

The findings provide insights into the effects of dynamic loads on transmission shafts, gears, and bearings. Torsional vibrations are the most damaging factor, contributing to fatigue cracks, increased contact stresses, and energy losses [1,7].

Elastic and inertia dampers significantly improve operational efficiency. Maximum shaft torque amplitudes decreased by 50–60%, enhancing fatigue limits and reducing the likelihood of microcracks. Engine rotational stability improved, energy efficiency increased, and fuel consumption decreased [6,8].

Damper effectiveness depends on stiffness, inertia, and damping properties. Incorrectly chosen dampers can exacerbate resonance, underlining the importance of simulation-based parameter optimization [9,10]. Dynamic load intensity also depends on wheel load variations, road surface unevenness, and gear elastic deformations, highlighting the need to account for both static and dynamic loads in modern transmission design.

The combination of elastic and inertia dampers effectively shifts resonance frequencies, reduces critical vibrations, extends component service life, and minimizes bearing and gear noise and frictional losses. The study confirms that dampers are a scientifically justified strategy for improving transmission system stability, energy efficiency, and durability.

CONCLUSION

This study analyzed dynamic loads in the transmission systems of wheeled and tracked vehicles. Torsional vibrations, impulsive gear forces, and increased bearing stresses significantly reduce transmission operational stability. Elastic and inertia dampers effectively attenuate these vibrations, decreasing torque amplitudes by 50–60% and mitigating resonance effects.

Simulation results indicate that engine torque pulsations, uneven wheel loads, and elastic gear deformations collectively intensify dynamic loads. Therefore, transmission design must consider not only static loads but also dynamic and stochastic forces.

Optimally selected damper parameters — stiffness, inertia, and damping coefficient — extend component life, reduce bearing and gear noise, enhance energy efficiency, and stabilize system operation. Implementing scientifically grounded strategies to reduce dynamic loads, including dampers and computer modeling, is crucial for improving vehicle reliability and operational efficiency.

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