RELIABILITY FUNCTIONS OF ELECTROMECHANICAL POWER STEERING

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ABSTRACT

The vast majority of new automobiles are equipped with electromechanical power steering systems (EPS). These systems have clear advantages over hydraulic or pneumatic designs. At the same time, the service life of the EPS has not been fully studied. The EPS is a combination of electronic and mechanical subsystems, which puts certain limits on the application of existing diagnostic methods and tools typically used to monitor the performance and current health of a motor vehicle. This situation adds urgency to the development of standards for managing the health of motor vehicles based on diagnostic information, to organizing research results in this area into a system, and generally addressing the problem of improving the operational reliability of EPS systems. The results of the study should be helpful in developing a methodology for managing EPS reliability and fault-free operation. The background of the problem, objectives and methods are described in Part 1 of the article published in World of Transport and Transportation, Vol. 15, 2017, Iss. 4.

Keywords: automobile, steering system, electromechanical power steering, equipment health management, reliability, operation.

Key faults and failures

It is demonstrated in [1] that electric equipment accounts for the greatest share (22–30 %) of the total number of defects in a motor vehicle, or 224–318 faults per thousand automobiles. It is also notable that units incorporating electromechanical energy converters (starters, EPS, generators, electric motors) are responsible for a significant share of operability interruptions (40–45 %). Thus, a failure of the electromechanical power steering system is one of the most frequently occurring faults of VAZ-21703 cars.

However, EPS faults and malfunctions haunt not only domestically made cars.

For example, [2] contains information on EPS failures in KIA ceed, Mazda 2, Mazda 6, Hyundai Verna caused by defects in the torque sensor. In Mitsubishi Lancers, an error in the electronic controller's algorithm was the key cause of EMS failures. The EPS unit used in Hyundai Elantra is known for knocks in its gear.

A probable resistor damage in the printed circuit board of the EPS system caused a recall campaign for Toyota Highlander vehicles sold in the Russian Federation on and after 10 October 2014. It is noted that the recall campaign covered 4,279 vehicles.

General Motors recalled 6.3 thousand Chevrolet Caprice Police Pursuit sedans delivered to police units in the USA from 2014 to 2016, on concerns that the vehicles could be furnished with defective power steering systems that would turn themselves off in traffic [4].

Going back to the reliability of EPS systems built in the Russian Federation, it should be noted that only 50 % of EPS systems installed in the first batches of Lada Kalina cars functioned properly. About 35 % of the cars were fitted with inoperable EPS systems. The remaining 15 % still had some serious faults such as cases of steering system seizure or spontaneous rotation, etc. [2].

Dissertation [5] includes a study of a warranty case database for Lada Granta cars. Based on the study's findings, the author concludes that the EPS system comes out as the least reliable unit in the vehicle's electrical system. Its reliability indicator stood at 47.7 %, accounting for approximately 18 % of the total number of failures in the electrical system.

Thus, the problem of the EPS's low reliability in operation necessitated research efforts targeted at such aspects as design of the EPS unit, control algorithms, and the methods used for command generation by the electronic control unit in response to external inputs. The overall goal of such research projects was to identify factors causing the EPS system to lose operability. As a result of completed research projects, a variety of hypotheses were proposed.

Thus, [6] notes that electromagnetic impacts on the sensors and control units of gearless EPS systems cause a negative effect on the system's proper functioning. In particular, in the event that a sensor incorrectly identifies the pull-in torque $M_{p\text{-}in}$, the electronic control unit generates a command to create an extra balancing torque M_{bal} on the steering column, which leads to spontaneous rotation of the steering wheel in traffic and uncontrolled turning of the steerable wheels.

In the event of a firmware error in the ECU's microprocessor, control signals get distorted, and as a result the on-board diagnostic system cannot determine whether the unit is sound and issues a command to disable it. In addition, electromagnetic impacts on the EPS system may affect the vehicle's steerability, thus making maneuvers more difficult for the driver.

It is shown in [7] that inferior reliability of gear-based EPS leads to the following faults:

– seizure of the steering mechanism;
– fracture of the steering rack;
– spontaneous rotation of the steering wheel;
– knocks in the steering gear when the steering wheel is turned;
– failure of the torque sensor;
– failure or malfunction of the ECU.

It is becoming increasingly urgent to research the above defects of the EPS systems and develop modern methods of diagnosing the health of this system. An important aspect of this task is that the existing diagnostic functions (the onboard diagnostic capability with a light indicator and diagnostics with a tester/scanner) do not afford the possibility of tracking changes in the mechanical part of the EPS system in a detailed manner [8]. Moreover, such issues should be addressed in an authorized maintenance center

[1]Part 2 (final). For Part 1, see World of Transport and Transportation, Vol. 15, 2017, Iss. 4, pp. 58–69.

only. It is impossible for the common user to perform diagnostic procedures correctly [7].

Diagnostics of gearless power steering systems

International researches have been studying EPS systems since the early 90s of the last century, and these efforts are reflected in a large number of patents covering EPS designs and control methods. The significant contributions of the Japanese researchers Yasuo Shimizu, Atsuhiko Yoneda, Hitoshi Shiobara, Takashi Kuribayashi, Hirofumi Matsuoka to addressing design challenges of various EPS systems should be noted [9].

The body of research results accumulated to-date by domestic researches in the field of studying various design parameters and performance characteristics of EPS systems can be divided into two distinct categories: theoretical and experimental.

In the group of theoretical research projects, results obtained by V. N. Kozlovsky and R. A. Maleyev addressing various aspects of EPS design and manufacturing should be recognized on top of the others.

Thus, in [10] the researches discuss mathematical models that are capable of predicting the system's reliability. The authors note that in order to ensure high quality of the end product, qualitative assessment of the key parameters of the units to be manufactured must be performed. Variations in the size parameters of the units may lead to significant changes in EPS performance characteristics.

Work [11] focuses on building a mathematical simulation model in the Matlab environment, which model translates information on EPS failures into reliability indicators. As a result of their analysis, the authors established that the greatest proportions of EPS defects were caused by faults in the electronic control unit and torque and rotor position sensors, while a significant number of faults is related to deviations of the EPS active elements' size parameters from the required specifications.

Papers published by the Novosibirsk researchers B. M. Bochenkov, G. L. Nikulina, M. V. Tyurina, G. A. Frantsuzova and others reflect on particular design features and methods for the improvement of EPS control units.

Thus, in [12] the authors present key electronic components used in EPS systems, providing detailed descriptions of the structural design and key operating principles of the unit manufactured by Avtoelektronika OJSC, Kaluga – the primary supplier of EPS systems to AvtoVAZ.

Work [13] proposes a method to increase the dynamic steering accuracy of EPS systems. The method is based on two solutions: algebraic generation of the control signal that determines the electric motor's compensation torque using measured values, and an improved design of the measuring system.

In [9], aspects are considered of improving the functional efficiency of the EPS system through the use of precision elements of the measuring system. The author suggests an algorithm for generating the EPS output torque signal, which algorithm ensures high levels of both static and dynamic accuracies. The author defines a criterion for evaluating the quality of the EPS system in the course of comparative testing. The criterion is used to establish the position-following error within a given range of frequencies. An EPS design is proposed where the torque sensor relies on the magnetoelastic effect to improve the accuracy of torque measurement and replication in processing the response from the road at frequencies of up to 20 Hz as compared to similar existing designs.

In the lineup of research papers, we should note some that address particular challenges encountered at the stages of EPS systems' design, modeling, computation, and review of functioning.

For example, the research reported in [14] focused on mathematical modeling of magnetoelectric valve motors for EPS systems used in passenger cars.

Details involved in the development of a functioning logic diagram for EPS systems based on frequency-controlled asynchronous motor, as well as in its implementation and principles of operation are discussed in [15].

Work [16] reviews the existing types of stepper motors and provides analyses of their design features, with a view to using analog electric motors in EPS designs. The paper defines the requirements to the parameters of the electric motor to be chosen in view of the assigned levels of external loads. Formulas were developed to compute the torque of the stepper motor that is used as the effector element in either ball screw or rack-and-pinion EPS systems.

Findings of experimental studies of gearless EPS systems are reflected in [17, 18]. The authors had developed and built a dedicated test bench, connectors, control boards, indicators, and a control panel. The test rig is intended for verifying the electrical and mechanical parameters of EPS systems.

The experimental test bench allows conducting EPS tests in automatic and manual modes at temperatures from minus 40°C to plus 50°C and relative air humidity of 95±3 %. Loading cycles are proposed to be used as testing modes. One cycle is assumed to be a simulation of alternating rotations of the motor's input shaft to an angle that corresponds to three revolutions of the automobile's steering column to the left and three to the right. The test rig generates input information for the ECU, namely the signals from the rotor position sensor and the speed sensor. In addition, the test rig allows to set various load values of the torque at the output shaft: 12, 20, 32 Nm, and two speeds: 5 km/h and 10 km/h. The publication notes that the test rig is in practical application at PO Sever Production Association.

Diagnostics of gear reducer-based electromechanical power steering systems

V. V. Korolyov has made a prominent contribution to the theory of gear reducer-based EPS [19]. The author developed and proposed:

– a generalized model of the EPS system. The model is distinct from others in that it takes into account the impact of the automobile's parameters and the parameters of the EPS system's switch reluctance motor. The model makes it possible to design EPS systems using the methodology of controlling the compensatory action;

– an original interpretation of interconnections between the steerable wheels' reactions, torques in the EPS, and the compensatory torque created by the switched reluctance motor in order to determine the necessary compensatory impacts to be exerted by the electric drive in the process of the EPS-equipped automobile's motion;

– a mathematical model of the switched reluctance motor that is distinct from the previously known models in that it is less labor-intensive in terms of computer modeling, and allows a more efficient construction of the EPS drive due to a more accurate interrelation between the specific conductance of the

air gap and mutual positions of the teeth of the stator and the rotor;

– an EPS system that improves the performance of the automobile and the quality of handling.

Research performed by V. I. Domanov, A. V. Domanov and their colleagues that studied issues in controlling the operation of the EPS system. The authors propose a system featuring a correction unit that accounts for the motor vehicle's operating conditions and personal traits of the driver. The correction feature relies on a driver-related signal, and an adjustment signal proportional to the speed of the automobile. It is noted that the use of the forward-looking correction mechanism has the potential of more than doubling the EPS stability zone relative to the traditional EPS system architecture [20].

Work [21] analyses the impact of external factors on the EPS system. It demonstrates that, in order to reduce the driver's workload and the resistance torque exerted by the road, the characteristic of the torque sensor needs to vary depending on the speed of the automobile. Such a variable characteristic can be achieved with either analog or digital methods.

Work [22] studies the operation of the EPS system in the presence of stray/random signals, and compares various EPS control structures by output signal dispersion levels.

The principles of EPS functioning in the modes of city traffic, freeway traffic, and parking maneuvers are presented in [23]. Another publication [24] offers a comparison between design features of an electrohydraulic power steering system and a Servoelectric EPS. The research objective of [25] is to develop a model of the complete steering system of a car equipped with an EPS. The authors offer a function block diagram of an EPS with a reducer and a switched reluctance motor.

Research paper [26] should be noted as it determines the key functions performed by the EPS electric motor's control system. A set of controls is incorporated in the electric motor's control algorithm, whose correct implementation can be achieved through the use of a 32-bit microcontroller offered by the company Atmel. This microprocessor's features meet all the requirements to EPS systems of category M1 automobiles.

Perfecting the ECU operating algorithms is among mainstream areas of research. Thus, [27] analyses the microcontroller's algorithm for the purpose of better understanding the behavior of the EPS-equipped motor vehicle. The Matlab environment was used for modeling. As a result, theoretical dependencies were established of the resultant and compensatory torques on the turning angle of the steering column and the speed of the automobile. Article [28] summarizes an EPS analytical research project and synthesizes control algorithms by developing mathematical and digital models.

V. S. Moulgin [29] worked to create a new model for the input torque sensor whose principle of operation relies on the Hall effect. The author suggests that the torque applied to the steering column be measured based on the dependence of the change of distance between the Hall sensor and a magnet on the degree of the torsion bar twist.

A. I. Arkhipov [30] conducted experimental studies of the EPS input torque sensor's characteristics. Based on the results obtained with an automated test rig, the researcher finds that the sensor's output signals transmitted on two channels have the shape of a meander with a frequency of 2 kHz and an amplitude of 5 V. Depending on the torsion bar's twist angle, the duty cycle of the signals varies between 20 and 80 %, and in the absence of torque on the input shaft, the duty cycle value is 50 %.

Currently, the world's leading automakers are developing shaftless EPS systems. A shaftless system is construed as a system that has no mechanical linkage between the steering column and the steering mechanism, i.e. a system that relies on the so-called «drive-by-wire» technology. In terms of its design, a shaftless EPS system is one that has two coordinated electric drives, one on the steering column and the other on the steering rack, with no mechanical link between them. One of the two operates in the tracking *mode and turns the steerable wheels according to the signal from the steering wheel's position sensor. The other drive determines the torque on the steering column in proportion with the torque on the shaft of the steering mechanism, thus 'sensing the road' and returning the steering wheel to the neutral position when the steering wheel is released (the self-resetting feature) [31].*

It is noted that the system under development has a number of advantages, such as:

– no rigid structural linkage of the motor vehicle's cabin and the steering mechanism to steerable wheels;

– the possibility of controlling the automobile with assistance from electronic systems, including an on-board computer;

– a compact size in comparison with traditional shaft-based power steering systems;

– low labor-intensity of maintenance and repair due to a smaller number of mechanical parts.

Numerous domestic and international automakers are working to develop drivebywire steering systems. However, there exist neither serially produced models nor publications disclosing the design principles or elements of systems under development [32].

Conclusions

The overview presented above shows that fitting motor vehicles that fall into the M1 category with electromechanical power steering systems remains a promising direction in the development of the automotive industry.

The overview identifies the key requirements to the EPS system, defines the key tasks that the system should address, considers various designs and functional features of the system as an element of a motor vehicle, and offers an analysis of the domestic experience in developing such systems and preparing them for serial production. For a number of reasons, modern automobiles are equipped primarily with columnar gearless EPS systems.

The overview summarizes the most prominent failures and faults of the EPS that occur in the course of the system's operation, and demonstrates that a built-in diagnostics system of a mechatronic unit is unable to track changes in the health of the unit as part of its operation.

Our analysis of the results obtained in the theoretical and experimental studies of both gearless and gear reducer-based EPS has provided evidence that developers tend to give more attention to various aspects of the design, operation, predicting and modeling of the unit's characteristics and individual elements of the EPS system. This definitely brings into the foreground the problem of the system's operational reliability, and makes indispensable continued research efforts in these areas with a stronger focus on quality-related characteristic of EPS systems.

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