A REVIEW ON THE EFFECT OF FUNCTIONAL PARAMETERS ON THE FRICTION, WEAR AND DURABILITY OF AUTOMOTIVE PIVOTS AND SPHERICAL COUPLINGS

Andrei-Marian ZĂHĂRESCU[1], **Ilie MUSCĂ**[2]

1 Faculty of Mechanical Engineering, Automotive and Robotics,"Stefan cel Mare" University of Suceava, marian.zaharescu@usm.ro.
2 Faculty of Mechanical Engineering, Automotive and Robotics,"Stefan cel Mare" University of Suceava, iliem@usm.ro.

Abstract: *The increase in the number of passenger and commercial vehicles, together with the growing number of safety regulations, will increase the demand for ball joints in the years to come, making it important to study the in-service behavior of these elements. Severe deterioration phenomena occur as a result of the interaction of many different factors such as external loads, duration of loads, temperature, corrosion. In this paper, a general classification of spherical couplings in automotive construction and a presentation of studies and literature articles analyzing the service life and deterioration of spherical couplings and pivots as well as experimental or industrial stands used has been made.*

Keywords: *ball joint, spherical couplings, wear, friction*

1. Introduction

According to SAE International's Dictionary for Automotive Engineers, [SAE,2023], the pivot is fundamentally defined as a joint composed of a sphere/ball and a housing. Ball joints allow only free rotation.

Ball joints can be found in the human body as well as in industrial applications.

This paper will further details concerning the construction of modern pivots (classification, calculation and design elements) and some aspects related to friction and wear. Automotive pivots are critical components and have been the subject of a lot of research and development since 1950 when they were designed and used in MacPherson suspensions in Ford Consul cars, [Rob Siegel,2017].

2. The economic importance of pivots

Factors such as increasing demand, for passenger and commercial vehicles linked with the growing number of safety regulations, will determine the request for automotive ball joints in the coming years. According to estimations, [Dataintelo,2024], the global automotive ball joints market is estimed to reach USD 1.8 billion by 2030, growing at a CAGR of 3.6% during 2022-2030.

3. Types of ball joints in a vehicle

The **ball joints** can be found in 3 main sub-assemblies **in a vehicle**:

a. Suspension System / Steering Wheel Pivot (SBJ);

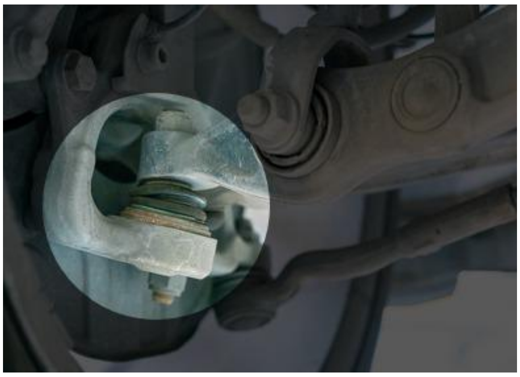

Figure 1: *Steering wheel pivots*

b. Steering system/ Tie rod(TR);

Figure 2: *Steering rod*

c. Suspension System/Stabilizer Link (SL).

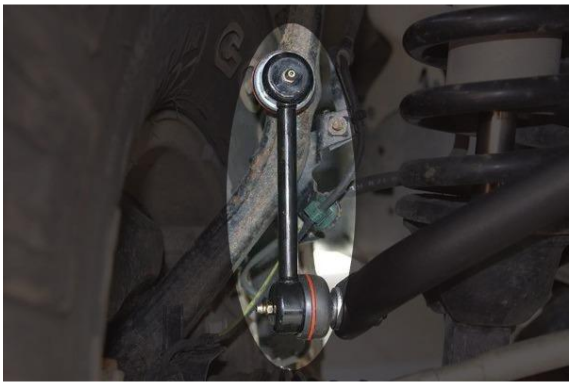

Figure 3: *Anti-roll bar*

Analyzing the data from the literature [THK,2024], [SOMIC,2024] as well as the catalogs of pivot manufacturers, a synthetic classification can be made, according to the different criteria taken into account, shown in Figure 4.

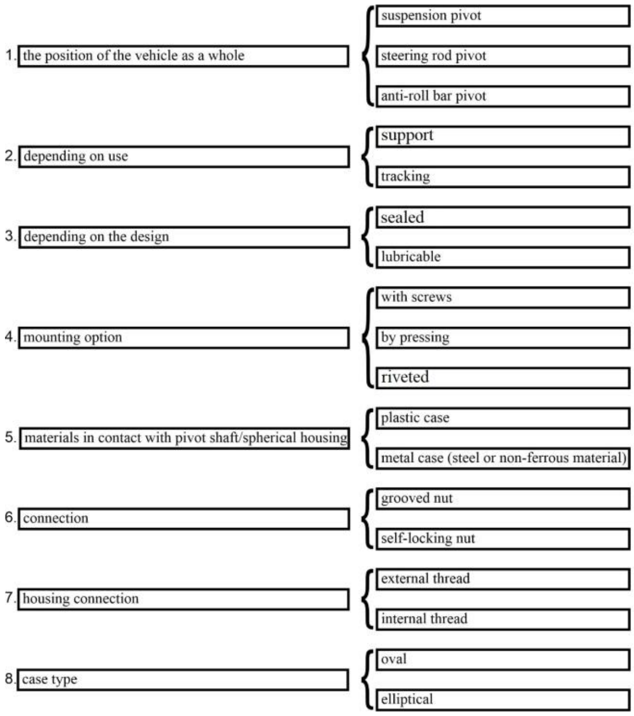

Figure 4: *General classification of ball joints in automotive construction*

Automotive pivots and other automotive **ball joints** are safety parts, and their deterioration has serious effects, that can lead to reduced vehicle control and command accuracy, in serious accidents. It is estimated that the average life of a **ball joints** is about 130,000 km for modern automobiles [Dataintelo,2024] but can be significantly less for older cars.

4. Standards and specifications

Ball joints and pivots are subject to national or international standards relating to:

a. Dimensions

The main dimensions are subject to national (DIN, JIS, etc.) or international (ISO, EN, SAE, etc.) standards, which regulate only overall dimensions, the internal design being the responsibility of the manufacturers who optimize them for each application.

b. Test

The AK-LH 14 specification is considered as a reference document for both manufacturers of pivots and users and covers the functional, strength and durabilitytests required for acceptance of pivots.

c. Certifications

The "AMECA Automotive Ball Joint Certification Program SC05A", [AMECA, 2019] is offered by AMECA being an independent organisation in the United States that certifies the product, in this case the ball joints, meets the applicable quality standards following a rigorous process of tests and audits.

5. Studies and research on ball joints and pivots

The interest of the research carried out is justified by the importance of the applications of **ball joints** and especially of pivots as well as the interest of component manufacturing companies and car manufacturers to offer safe and reliable products.

The study of automotive ball joints has been addressed in various research papers, which analyze the following the effect of different technologies applied to the components in contact to reduce friction and improve durability, the materials used and the constructive solutions adopted.

5.1 Effect of coatings on performance

Friction as well as its effects in ball joints with active surfaces coated by various methods were studied.

Results obtained with active surfaces coated with Diamond-Like Carbon, DLC, [Komori, 2015] show that this type of coating is beneficial in reducing friction but can only be applied for special applications given the very high cost of this coating, not being applicable for mass production.

The presence of polytetrafluoroethylene (PTFE) coating on the ball could considerably reduce the sliding friction in the joint [Zhang,2015]. The PTFE coating debris served as a lubricant and prevented rapid wear of the parts. As a result, the movement of the joint could remain stable for a certain period of time.

Coating with Rilsan, Loctite, by anodic oxidation, offers good wear resistance before failure. In terms of fabrication, Rilsan coating and anodic oxidation are easier to achieve, [Castagnetti,2015]. The number of cycles after which damage to the pivots occurs depending on the type of coating used, Rilsan 22,925 cycles, Loctite 14,321 cycles and anodic oxidation 35,260 cycles.

The performance obtained by galvanizing differs depending on the thickness of the coating layer of the spherical end of the pivot pin, [Chung, 2020]. The results of the abrasion tests revealed firstly the axial clearance of the ball joint is negatively influenced by the irregular thickness of the coating layer, which causes an increase in the coating layer and, implicitly, an accelerated wear. Secondly, the performance of the joint in abrasion tests varies with the thickness of the spherical end cap coating layer, and coating with a thicker layer was found to be less favorable in terms of durability and the solution of an uncoated pivot is the best option.

In conclusion, surface coatings of the contacting elements in a spherical coupling can have beneficial effects on reducing friction and increasing durability. These coatings should be adopted with caution and carefully studied in terms of economic costs and thickness of the coated layer, as a thicker layer leads to increased wear.

5.2 Friction in spherical couplings and pivots

Mathematical models of spherical joints with friction have also been developed. The results obtained for a range of different values of the coefficient of friction [Sage, 1987, (on different material couples) confirm that the joint axis tilt angle/direction of force application is a critical parameter.

As a result of tribological tests carried out on the coupling of carbon steel material and plastic material of the spherical part, the friction in the spherical and pivot couplings of the contact between the ball of the pivot pin shaft and the spherical joint was studied [Watrin,2017] and the variation law of the dry contact wear coefficient at different sliding speeds and loads was identified. The determined wear coefficient is approximately $3{,}10^{-10}\mathrm{mm}^2\ \mathrm{N}^{-1}$.

One parameter present in the pivot testing standards is the breaking moment. By this parameter is meant the moment required to move the axle at the first relative displacement after it has been assembled. The rotational breaking moment has to reach a specified value before proceeding to the wear test and the radial elasticity has to meet the specifications, both before and after the test, [Omar,2017], the subject developed in the paper is essential for evaluating the differences before and after the wear tests.

A study of the dependence of pivot friction on clamping force lubricated or not lubricated was presented in [Musca,2019]. The tests were performed on an original test rig that allows the measurement of the frictional moment in the spherical coupling at various values of the clamping force, between the ball and the spherical support, when the spindle moves. These results showed that the value of the moment increases with increasing pressing force but also if the lubricant is present or absent. Considering the fact that the pressing force in a real pivot is not adjustable and is determined by the closing mode, it follows that the manufacturing technology and the dimensional chain of the coupling can influence the pressing force from the pivot and implicitly the friction.

A comparison of the friction coefficient values inside ball joints is presented by [Wozniak,2014]. The friction coefficient values decrease as the loading force increases. The friction coefficient values decrease as the applied loading force increases. As the load increases, the analytically determined friction coefficient value approaches the one obtained through experimental measurements on the stand. The differences between the two methods are minimal, with a maximum variation of no more than 0.0025 across the entire load range.

An analysis of grease lubricated ball joints [Radulescu,2019] shows the influence of the eccentricity ratio on the pressure distribution profile. This is essential for the full spherical bearing, its load carrying capacity increasing with increasing eccentricity ratio and maximum angle, while for the partial spherical bearing the load carrying capacity increases with increasing eccentricity and decreasing minimum bearing angle.

It can be concluded that the frictional moment in a spherical coupling depends on the conditions in the joint. It is influenced by several factors, including the angle between the axis of rotation and the direction of the applied load. Additionally, the coefficient of friction plays a significant role. The size of the contact area between the pivot ball shaft and the spherical shell in the socket also affects the frictional moment. The magnitude of friction in a spherical coupling decreases by about 50 % when the contact is lubricated.

5.3 Life of spherical couplings and pivots

Studies and research aimed to predict fatigue life are presented in [Kozłowski,2021]. The results obtained from tests on a test rig on which the fatigue durability of a steering rod pivot can be determined, allowed the estimation of the limit number of loading cycles after which the ball joint of a 3.5 tonne vehicle no longer meets the safety requirements, exceeding the set value may have consequences.

Vehicle manufacturers' design assumptions indicate that for steering system components containing ball joints the requirement is that they must be operated without failure until approx. 160 000 km on Servotest type stands. The kilometers are counted by simulating the vehicle's operating conditions so that the steering system components, including ball joints, are subjected to a durability test under controlled conditions under various load conditions resulting from vehicle acceleration – braking, cornering, as well as rough road. Based on the bench test, the fatigue durability of a pivot in a steering rod can be determined, estimating the limit number of load cycles after which the ball joint does not meet safety requirements.

5.4 Damage to spherical couplings and pivots

Pivot damage by pulling the pivot assembly out of the support was analyzed [Baynal,2010]. As the results obtained, the dimensions of the housing and pivot were redefined, and the required pullout force was determined to be greater than 2000 kgf.

The results obtained by [Ossa,2011] show that the fracture occurred due to fatigue, generated in the ball pivot and bushing contact area with the spherical locus, accelerated by the large amount of ferrite resulting from an inappropriate heat treatment applied to the pivot shaft, and another factor contributing to the damage was the improper design, characterized by sudden section reductions.

The behavior of the sealing bellows was modeled by [Chen,2011]. The comparison between the numerical results and the real bellows at different oscillation angles shows that the FEA model can predict, the stress and deformation of the bellows.

Deterioration of the pivots of a heavy vehicle can be attributed to long-term wear. According to the results of the study, [Zhenyu, 2021] the sealing bellows undergoes aging and cracking process during use, which leads to damage of the pivot axle and corrosion of the ball end. In addition, loss of lubrication increases friction and bending moment, thus causing fatigue failure under cyclic loading. This phenomenon is a typical example of pivot wear, ageing and fatigue.

Friction-induced vibrations in pivots were investigated by [Kang, 2022] using an approach that highlighted that the unstable frequencies of the linear ball-and-socket joint model do not correspond to the squeak frequencies obtained from the nonlinear numerical response. In the nonlinear analysis, a fundamental frequency appeared in the periodic motion, and the tilt angle of the reaction prestress was identified as the determining factor of the oscillation pattern. The periodic motion transformed into a quasi-periodic and, subsequently, chaotic behavior as the angle increased. Another result shows that the spectral frequencies and squeak oscillations of the ball-and-socket joint change significantly with the tilt angle.

5.5 Experimental stands used for the study of spherical couplings and pivots

Most existing installations for testing ball joints are limited to a maximum of five axes, loads on the 3 axes + rotational movements only on 2 axes. To simulate real loading conditions, it is necessary to use a six-axis test bench, i.e. loads/forces applied on the 3 axes + rotational movement on all 3 axes.

The use of test benches allows:

-reducing the company's costs for performing tests in external laboratories;

-improving the operational design for new products;

-shortening the duration of the production preparation process when developing models;

-reducing the complexity in determining the causes of defects without dismantling the assembly.

6. Conclusions

Severe damage phenomena in spherical couplings occur as a result of the interaction of many different factors, such as external loads, duration of loads, corrosion. In the case of failure of the ball shaft in a pivot, especially in heavy-duty applications, the failure mode is a unidirectional bending fatigue fracture. Most failures in ball joints are caused by corrosion and contamination causing excessive wear.

References

1. SAE International’s Dictionary for Automotive Engineers, John Kershaw, SAE International, 2023
2. Rob Siegel, *Ensure your classic car’s ball joints are dependable, Maintenance and Tech, 2017* available from, https://www.hagerty.com/media/maintenance-and-tech/dependable-ball-joints/)
3. Data Intelo, Global Automotive Ball Joint Market, available from,

https://dataintelo.com/report/global-automotive-ball-joint-market/

4. AMECA Organization Certification Program available from, https://ameca.org/wp-content/uploads/2019/09/SC05A-AMECA-Ball-Joint-Certification-Program-R6.pdf
5. Komori, K.; Nagataki, T. *Friction behavior of diamond-like carbon coated ball joint: Approach to improving vehicle handling and ride-comfort*. SAE Int. J. Passeng. Cars-Mech. Syst. 2015, 8, 638–646.
6. Chung, Soo Sik , s.a *Practical evaluation of ball stud plating effects on the increase of free gap of ball joints in the vehicle*, International Journal of Automotive Technology, Vol. 21, No. 5, pp. 1107-1111 (2020)
7. Zhang,Jie s.a *Practical evaluation of ball stud plating effects on the increase of free gap of ball joints in the vehicle,* 2nd International Conference on Machinery, Materials Engineering, Chemical Engineering and Biotechnology (MMECEB 2015)
8. Castagnetti D, s.a *A novel ball joint wear sensor for low-cost structural health monitoring of off-highway vehicles*, Mechanics & Industry 16, 507 (2015).
9. Musca, I.; Românu, I.C.; Gagea, *Preliminary study of friction in automotive ball joints*, Proceedings of the IOP Conference Series: Materials Science and Engineering, Proceedings of the International Conference on Tribology (ROTRIB’19), Cluj-Napoca,RO, 19–21 September 2019; Volume 724.
10. Shahrizal Bin Omar, *Tribology Study of Suspension and linkages in automotive*, Mytribos Symposium 2 (2017) pp.38-40
11. R. M. Sage *The mathematical modelling of ball joints with friction*, Doctor degree thesys, Leicester, UK University
12. Watrin, J.C, sa, *Analytical modelling of the ball pin and plastic socket contact in a ball joint*, LEMTA, CNRS-UMR 7563, Lorraine University, LARIOPAC, 2011
13. Marek Wozniak, M, sa *A Study on Wear and Friction of Passenger Vehicles Control Arm Ball Joints*, Energies 2021,14,3238. Available from ttps://doi.org/10.3390/en14113238
14. Radulescu, A.V, sa *Theoretical Analysis of Spherical bearings Lubricated with Greases*, International Conference on Tribology (ROTRIB’19), 2019
15. Kozłowski E, sa *Predicting the fatigue life of a ball joint,* Transport and Telecommunication, 2021, volume 22, no. 4, 453–460 Transport and Telecommunication Institute, Lomonosova 1, Riga, LV-1019, Latvia
16. Zhenyu,W, sa *Analytical modelling of the ball pin and plastic socket contact in a ball joint*, Advances in Mechanical Engineering 2021, Vol. 13(10) 1–8_ The Author(s) 2021 DOI: 10.1177/16878140211052287 available from journals.sagepub.com/home/Ade
17. E.A. Ossa, C.C. Palacio, M.A. Paniagua *Failure analysis of a car suspension system ball join*, Engineering Failure Analysis 18 (2011) 1388–1394
18. Chen, A, *Investigating the Behavior of Ball Joint Sealing Boots Using a 3D Finite Element Model***,** ZF Lemforder Corp Journal
19. Kang, J *Nonlinear Vibration Induced by Friction in a Ball Joint System*, Lubricants 2022, 10, 201
20. Baynal, K, sa *Solution for failure analysis of automotive axle knuckle pull-out*, International Journal of Automotive Technology, Vol. 11, No. 5, pp. 701−710 (2010)
21. Shindle, J, sa *Design of Suspension Ball Joint Using FEA and Experimental Method* International Research Journal of Engineering and Technology (IRJET) Volume: 03 Issue: 07 | July-2016
22. Geren,N, sa *Automated sizing of automotive steering ball joints in parametric CAD environment using expert knowledge and feature-based computer-assisted 3D modelling,* University of Çukurova, Faculty of Engineering, Mechanical Engineering Department Adana, Turkey
24. S. Raes, sa, *Design of a tribological ball joint tester*, International Journal of Sustainable Construction and Design Ghent University, Belgium, 2015
25. Servotestsystem Company site available from 06_ball_joint_test.pdf (servotestsystems.com)