Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 15th International Scientific and Practical Conference. Volume I, 358-363

Stiffness Analysis of the Rubber Bushings of MacPherson and Double Wishbone Suspensions

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Abstract. **The rubber bushings are important components of automotive suspensions. These bushings play an important role in reducing noise and vibrations, enhancing ride comfort, and ensuring smooth vehicle motion. Therefore, investigating their elastic is of significant interest. This article presents the results of a force/torque analysis conducted on rubber bushings used in MacPherson and double wishbone front independent suspensions. To achieve this, three-dimensional geometric models of the rubber bushings were created using the SolidWorks software, employing two types of passenger cars as prototypes. The results were determined through Finite Element Analysis (FEA), and the radial force for all bushings was experimentally measured. The obtained results were then compared for validation.**

Keywords: FEA and experimental, rubber bushing, stiffness, suspension.

I. Introduction

Rubber bushings are commonly utilized as elastic supports in vehicle suspensions. The characteristics of these bushings are of paramount importance for conducting qualitative, frequency, and dynamic analyses, as well as for solving optimization tasks in suspension design and related components. Designing new bushings also requires understanding their deformation characteristics.

A significant portion of publications are focused on the design and optimization of rubber bushings [1]- [5]. Various analytical [3], [6], [7], [8] and genetic algorithms [1] are primarily used for design, aimed at determining optimal geometric parameters, with particular attention to sought-after characteristics of radial, axial, and torsional stiffness.

Various software products for Finite Element Analysis (FEA) are utilized in the design and determination of stiffness, with simulations analyzing stress and deformation changes [1]-[5], [8]-[11]. Publications employing FEA also explore the hyperelastic behavior of rubber (elastomers) [7, 12], utilizing well-known constitutive hyperelastic models such as Mooney-Rivlin [1],[5], [9]-[11], Marlow [9], Ogden [2, 10], and Neo Hooke and Yeoh in [11]. Comparison between constitutive hyperelastic models in FEA and experimental tests for rubber with varying hardness is presented in [10], while theories and execution of non-linear finite element analysis of elastomers and mechanical characterization testing of composite materials are discussed in [7], [12]-[14].

Experimental determination of bushing stiffness is also conducted, with methodology developed and dynamic stiffness and damping of suspension bushings defined in [15], and results for static stiffness presented in [8], [9],[11], [13].

FEA enables the construction, enhancement, and optimization of bushings before production; however, the analysis may not always be economically feasible due to requirements for increased computational resources, licenses for specialized software, and processing time.

Hence, determining the static stiffness of bushings from different suspensions remains a relevant task. Determination of stiffness is necessary for the accurate definition of fixation in various analyses [8, 16].

The purpose of this study is to determine the stiffness (through force/torque analysis) of rubber bushings used in MacPherson and double wishbone front independent suspensions. To achieve this, three-dimensional geometric models of the rubber bushings were created using SolidWorks software. Nonlinear FEA of the bushings was conducted, and the radial force for all bushings was experimentally measured.

II. Determining of the stiffness

The static stiffnesses of rubber bushings can be determined through mathematical equations when the

Print ISSN 1691-5402
Online ISSN 2256-070X
https://doi.org/10.17770/etr2024vol1.7993

material hardness is known, through FEA, and experimentally.

The most critical deformations include radial, axial, and torsional. Fig. 1 illustrates the deformations of a simple bushing, comprising inner and outer cylindrical steel sleeves and a rubber cylinder.

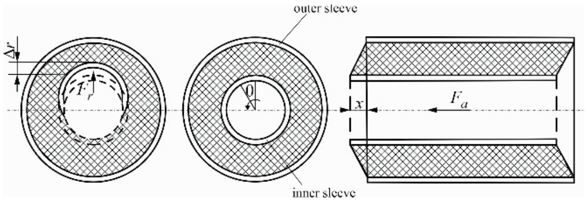


Fig. 1. Radial, torsional and axial displacements in bushing [1].

The stiffness of bushings can be obtained using analytical methods. Radial stiffness, specifically, can be determined by a specific formula [1], [7], [8]

$$K_r = \frac{7{,}5.\pi.L.G}{\ln\left(D/d\right)} k_l , \tag{1}$$

where k_l is the form factor and it is defined by the graphical dependence from [7], [8]; G is the shear modulus, MPa, it is defined by Shore hardness Hs, $G = 0{,}117 e^{0{,}034 Hs}$ or through the graphical representation $G = f(Hs)$ [7], [8], [10]; *L*, *D (R)*, *d (r)* are length, outer and inner diameter (radius) as shown in fig.1.

The axial stiffness can be determined by dependencies [7], [8]

$$K_a = \frac{2.\pi.L.G}{\ln\left(D/d\right)} . \tag{2}$$

General equation for torsional stiffness was developed by Adkins and Gent [6] and it can be determined

$$K_\theta = \frac{\pi.L.G.10^{-3} r^2 R^2}{R^2 - r^2} . \tag{3}$$

Determining the stiffness characteristics of the rubber bushings is also possible by constructing a mechano-mathematical model using the FEA. The hyperelastic constitutive models were first developed by Mooney (1940) and Rivlin (1948), and then from Valanis and Landel (1967), Treloar (Neo Hooke -1975), Ogden (1972; 1984), Gent (1992) and other authors.

The hyperelastic constitutive models describe the behavior of nearly incompressible materials and they are expressed in terms of function of the strain tensor invariants [1], [7], [9].

$$W = W(\bar{I}_1, \bar{I}_2, \bar{I}_3) , \tag{4}$$

where $(\bar{I}_1, \bar{I}_2, \bar{I}_3)$ are the invariants of the Green strain tensor.

The Mooney-Rivlin models are very popular and the form of the strain-energy potential for a five parameters model is determined by the dependence [9],[12]

$$W = c_{10}\left(\bar{I}_1 - 3\right) + c_{01}\left(\bar{I}_2 - 3\right) + c_{20}\left(\bar{I}_1 - 3\right)^2 + c_{11}\left(\bar{I}_1 - 3\right)\left(\bar{I}_2 - 3\right) + c_{02}\left(\bar{I}_2 - 3\right)^2 + \frac{1}{D_1}\left(J - 1\right)^2 , \tag{5}$$

where c_{10}, c_{01}, c_{20}, c_{11}, c_{02} are constants dependent on the type of material, determined based on experiments; J is volumetric deformation.

The three invariants are given in terms of principle extension ratios (nominal strains) λ_i, (i=1,2,3) [7];

Under uniaxial stress, the nominal strains are [7]

$$\lambda_1 = \frac{L}{L_0} \text{ и } \lambda_2 = \lambda_3 = \frac{1}{\sqrt{\lambda}} , \tag{6}$$

where L is the length after deformation; L_0 is initial length.

Under uniaxial stress, the nominal stress is determined by the relationship [7]

$$\sigma_1 = \frac{F}{A} , \ \sigma_2 = \sigma_3 = 0 , \tag{7}$$

where F is the applied force; A is the initial cross-sectional area.

The stiffness of the bushings is also determined through conducting experimental tests on stands developed for this purpose.

III. Materials and Methods

The study focuses on various rubber bushings found in the prevalent front independent suspensions of passenger cars. Fig. 2 illustrates the MacPherson suspension along with the stiffnesses of the rubber bushings mounted in the arm. Fig. 3 depicts the double wishbone suspension and the stiffnesses of the rubber bushings installed in the lower arm.

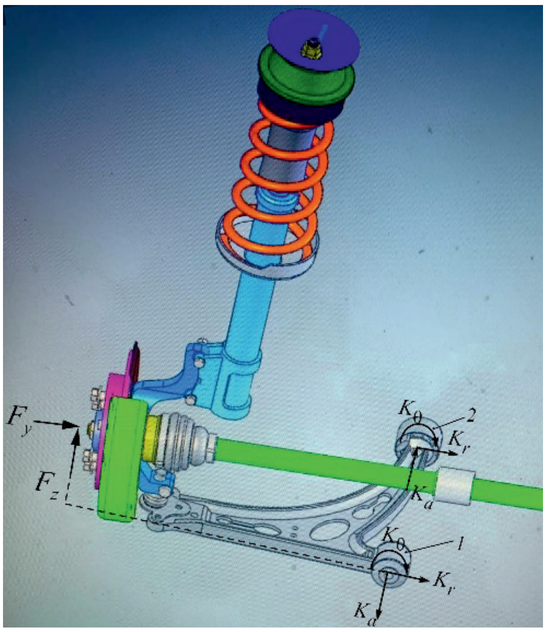


Fig. 2. MacPherson suspension and radial, axial and torsional stiffnesses in rubber bushings of an arm [16].

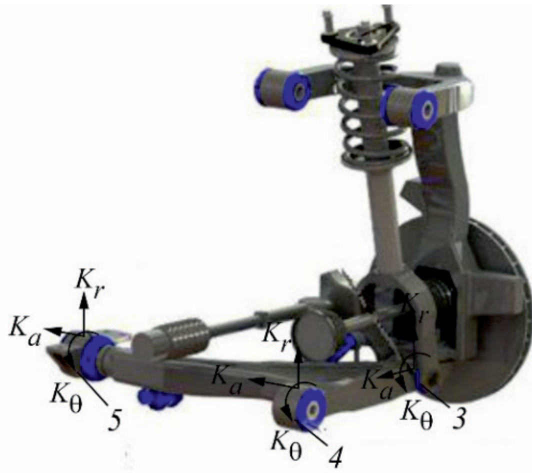
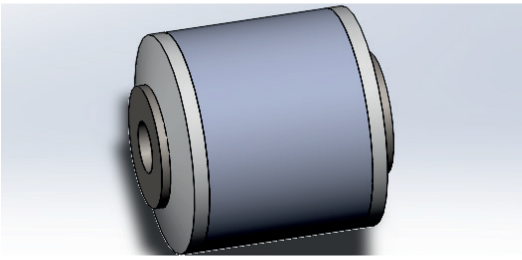


Fig. 3. Double wishbone suspension and radial, axial and torsional stiffnesses in rubber bushings of a lower arm.

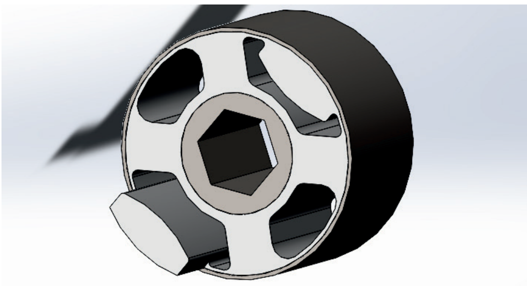
The rubber bushings models were developed using SolidWorks software.

Fig. 4 depict the three-dimensional geometric (3D) models of rubber bushings 1 and 2, respectively. A Skoda passenger car served as a prototype for their modeling.

Fig. 5 depict the 3D models of rubber bushings 3, 4, and 5, respectively. A Honda Civic passenger car was utilized as a prototype for modeling the bushings of a lower arm from a double wishbone suspension.

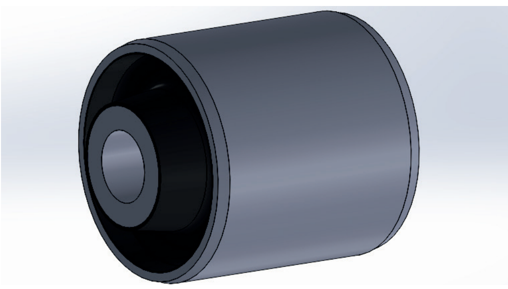


a) rubber bushing 1

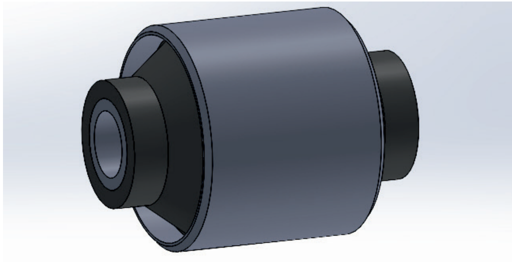


b) rubber bushing 2

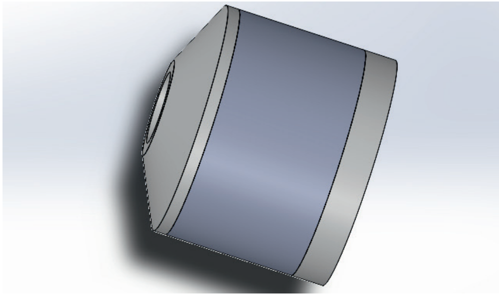
Fig. 4. Three-dimensional geometric models of the bushings.



a) rubber bushing 3



b) rubber bushing 4



c) rubber bushing 5

Fig. 5. Three-dimensional geometric models of the bushings.

The stiffness of the rubber bushings was determined through non-linear SolidWorks Simulation analysis. The elastic properties of the rubber bushings were estimated using the Mooney-Rivlin material model with five constants. Experimental stress-strain curves obtained from uniaxial tension tests for various hardness levels [10] were utilized as input for the automatic calculation of the five material constants performed by SolidWorks. A Poisson's ratio close to 0.5 was selected for rubber [7], and the density was assumed to be 1130 kg/m^3 [7]. The metallic components of the rubber bushings are fabricated of steel-normalized 4340, according to EN 10250. A three-dimensional curvilinear finite element mesh was employed for modeling the rubber bushings.

To determine the material constants of the bushings, their Shore hardness was initially assessed. The hardness of the bushings was measured using a Shore A Durometer tester. Fig. 6 illustrates the Hardness tester Shore A Durometer along with the rubber bushings. Table 1 displays the results of the rubber hardness for all the bushings.

Fig. 6. Tester Shore A Durometer and the bushings.

TABLE 1 HARDNESS OF THE BUSHINGS

Bushings	**Hardness, HA**
1	70
2	70
3	64
4	70
5	64

Compression tests of rubber bushings were conducted using an electric universal testing machine „WDW-20A“ (see Fig. 7). All bushings underwent three mechanical tests. To conduct the experiments, additional components were designed. The experiments were carried out at speed of 5 mm/min until a maximum force load (force) of the rubber bushings was reached.

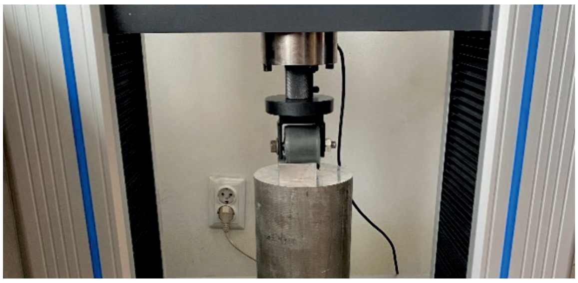
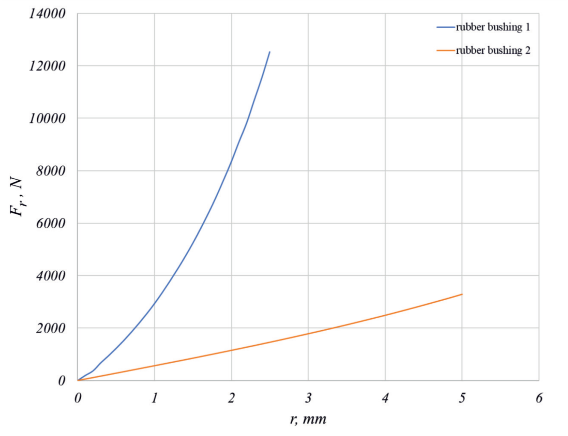


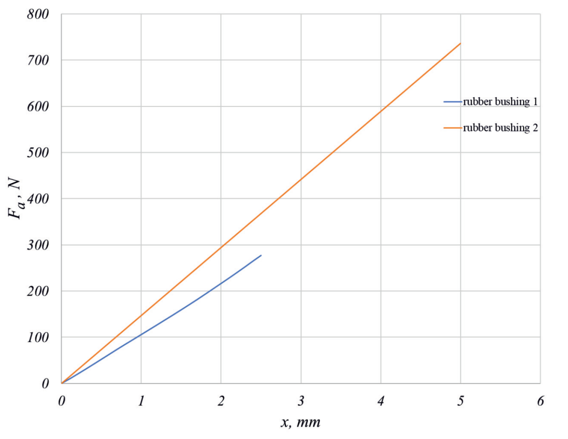
Fig. 7. Experimental test.

IV. Results and Discussion

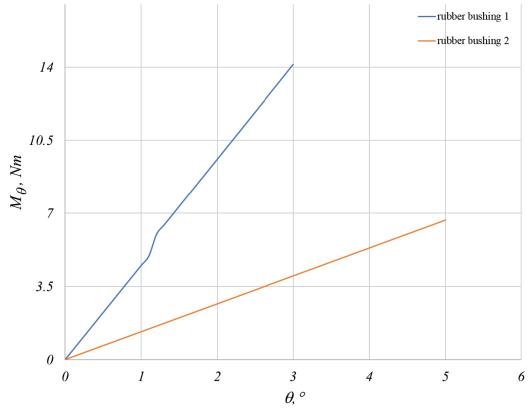
Fig. 8 illustrates the results obtained through FEA depicting the variation of load/torque with displacement/rotation for rubber bushings 1 and 2 in a MacPherson suspension. Fig. 9 displays the load/torque variation with displacement/rotation for rubber bushings 3, 4, and 5 in a double wishbone suspension.



a) radial loads

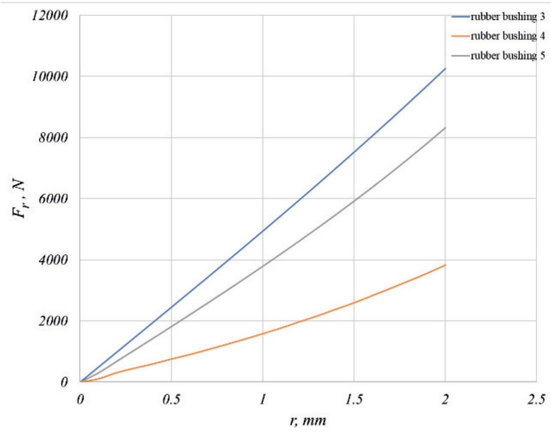


b) axial loads

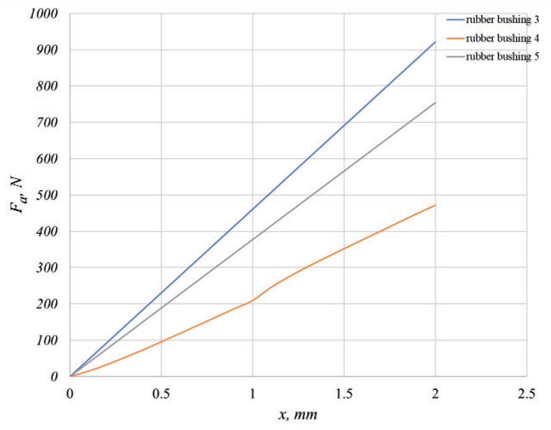


c) torsional moments

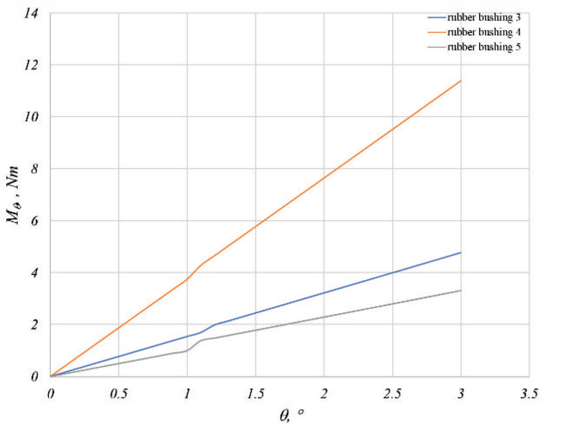
Fig. 8. FEA results for rubber bushings of MacPherson suspension.



a) radial loads



b) axial loads



c) torsional moments

Fig. 9. FEA results for rubber bushings of double wishbone suspension.

Fig. 10 presents the results obtained through FEA and experimentally for the variation of load with displacement of rubber bushings in one type of suspension. Similarly, Fig. 11 illustrates the results for the other type of suspension.

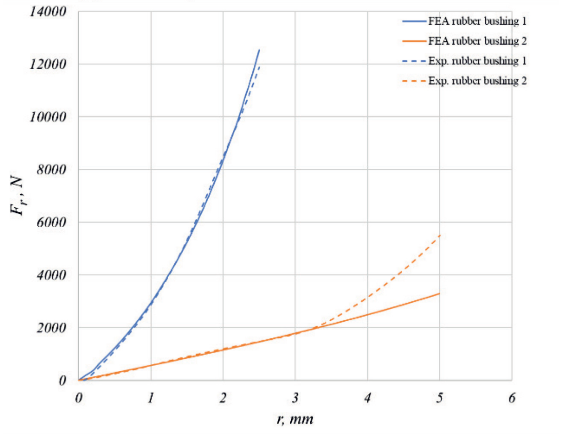


Fig. 10. Results for radial loads for rubber bushings of MacPherson suspension.

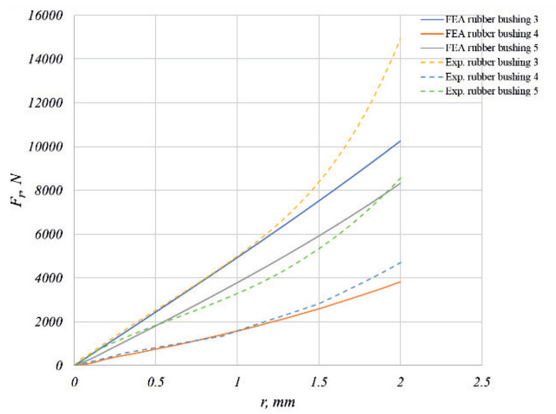


Fig. 11. Results for radial loads for rubber bushings of double wishbone suspension.

Table 2 presents the results for the radial stiffness of the bushings obtained by FEA, by experimentally and by formula.

TABLE 2 RADIAL STIFFNESS OF RUBBER BUSHINGS

Bushings	Radial Stiffness, (N/mm)			Deviation FEA and Exp,%
	FEA	Exp.	Formula	
1	3505	3694	5288	≈6%
2	567	596	1713	≈5%
3	5014	5532	4253	≈10.4 %
4	1743	1926	1619	≈10.4%
5	3959	3544	1303	≈10.5%

The results for radial stiffness determined by FEA are close to the results obtained experimentally, and analytically calculated ones differ significantly.

V. CONCLUSIONS

The study allows to make the follow conclusions:

The radial stiffness results obtained from FEA closely align with experimental results, with a maximum deviation of 10.5%.

When conducting experimental investigations to determine axial stiffness and torsional stiffness, deviations from both FEA and experimental results are expected to be of similar magnitude as those observed for radial stiffness.

For determining the stiffness of bushings with complex geometries, the FEA method is preferred.

The stiffnesses results obtained for the rubber bushings can be applied in various analyses, such as strength and frequency analysis of components and suspension assemblies.

ACKNOWLEDGMENTS

The authors would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support.

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