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Study of the Influence of Tire Air Pressure on Natural Frequencies of a MacPherson Suspension

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***Abstract*—The natural frequencies affect ride comfort and stability of vehicle. This paper presents the results of the natural frequencies of a quarter car MacPherson suspension system, obtained with different tire pressures and by using bushings made from different materials. The natural frequencies and mode shapes were obtained from finite element analysis (FEA) and the natural frequencies were also obtained by the using Fast Fourier Transform (FFT). To perform the analyses, an experimental study of the accelerations of various components of the quarter suspension was conducted. The experimental test was conducted of the MacPherson strut suspension system of an Audi A3 passenger car using a rubber bushing and a polyurethane bushing, mounted on the arm. The results were compared and analyzed.**

***Keywords*— FEA, FFT, MacPherson suspension, natural frequency, study, tire air pressure.**

I. INTRODUCTION

The suspension is one of the main vehicle systems that determines ride comfort, stability, road behavior and the dynamic loads transmitted to the vehicle body. During vehicle motion, road irregularities generate vibrations that are transferred through the wheel, arms, ball joints and bushings, spring and damper to the sprung mass of the vehicle. Therefore, the correct selection of the suspension parameters and the mechanical properties of its components is essential for ensuring both ride comfort and vehicle safety [1]–[6].

The vibration behaviour of suspension is commonly evaluated by parameters such as displacement, velocity, acceleration, damping, natural frequencies and mode shapes. Natural frequencies are of particular importance because they indicate the frequency ranges in which resonance phenomena may occur. When excitation frequencies caused by road unevenness or by the operation of a suspension tester are close to the natural frequencies of the system, the vibration amplitudes may increase significantly. This may lead to deterioration of ride comfort, reduced grip and increased dynamic loading of suspension components [1], [2], [7].

In many studies, vehicle dynamics are investigated using simplified quarter-car models, finite element analysis of the 3D models and experimental frequency response analyses [8]-[16]. The quarter-car approach is widely used because it allows the sprung and unsprung masses, suspension stiffness, damping and tire stiffness to be represented in a relatively simple mechanical model. At the same time, 3D suspension models using FEA allow the study of the natural frequencies and mode shapes of both individual suspension components and the entire suspension assembly with more realistic geometry and boundary conditions [8], [15]–[17].

The tire is an important component in the wheel–suspension–body system. Its radial stiffness depends on the tire construction, dimensions, vertical load and value of air pressure. A change air pressure affects the radial stiffness of the tire and, consequently, affects the dynamic response of the suspension system. For this reason, the influence of tire air pressure on the natural frequencies of suspension is important in the evaluation of vehicle vibration behaviour [2], [7], [18].

Another significant factor influencing the dynamic behaviour of the suspension is the elastic characteristics (stiffnesses) of the bushings. Rubber and polyurethane

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bushings are used to connect suspension elements and to reduce the transmission of vibration and noise to the vehicle body. However, different bushing materials have different stiffness [19]–[21] and damping properties. These differences may affect the natural frequencies, mode shapes and vibration amplitudes of the suspension components.

Various researchers have studied the stress and strain state, vibration behaviour and vibration response of vehicle suspension components using numerical and experimental methods [8]–[17]. Other studies have focused on the mechanical behaviour and stiffness characteristics of rubber and polyurethane bushings used in automotive suspensions [19]–[20]. However, the combined influence of tire air pressure and the mechanical properties of the arm bushings on the natural frequencies of a quarter MacPherson suspension requires further investigation.

The aim of this study is to determine the natural frequencies and mode shapes of vibrations of a quarter MacPherson suspension of an Audi A3 passenger car at different tire air pressures, using bushings with different mechanical properties mounted in the arm. The natural frequencies and mode shapes are obtained by finite element analysis (FEA), and the numerical results are compared with natural frequencies determined by processing experimental acceleration data through frequency response function (FRF) analysis. The obtained results are compared and analyzed to evaluate the influence of tire air pressure and bushing material properties on some of the vibration parameters of the suspension.

II. Materials and Methods

The natural frequencies of vehicle suspensions can be determined through solved the matrix equation by using various products – Matlab, Ansys, Abaqus and etc., and by processing of experimental data with different analysis.

The modes and natural frequencies of the system are derived from the solution of the equation

$$[K][\Phi] = [M]\,[\Phi]\,[\omega^2] \tag{1}$$

where [K] is nxn symmetric stiffness matrix; [M] is nxn symmetric inertia matrix; [Φ] is transformation matrix and contains the normal modes for i=1..,n, arranged as $[\Phi] =[\{\varphi_1\}\ldots,\{\varphi_n\}]$; $[\omega^2]$ is the diagonal matrix of the natural frequencies squared.

A. Methodology of simulation study

The focus of simulation is a quarter front independent MacPherson suspension. Fig. 1 illustrates simplified 3D model created with the SolidWorks program. An Audi A3 passenger car served as a prototype and the nominal air pressure of the front tire is 0.22 MPa and the value is recommended by the car manufacturer. Each geometric part of the suspension is individually modeled to form the assembly.

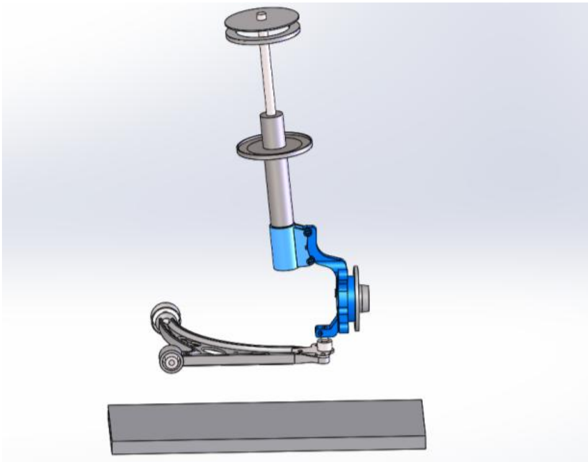


Fig. 1. Simplified 3D model of a quarter car suspension.

The natural frequencies and mode shapes of the quarter suspension was determined through frequency SolidWorks Simulation analysis. The necessary mass properties of the individual suspension elements are determined automatically by the program.

The static mass on one front wheel was measured using a suspension tester BEISSBARTH SA640. Suspension components are connected through local interaction and different types of connectors. Between hub and knuckle was used flexible bearing connector. The static stiffnesses of the bushings, spring and tire were presented by using spring connectors. The values of the polyurethane and rubber bushing stiffnesses were the same as [19]-[20]. The spring stiffness is 24 000N/m. The radial stiffness of the tire with dimension 205/55R16 were obtained experimentally using the laboratory setup of the flat bed tire testing machine [21] at different air pressures – 0.15, 0.20, 0.25, 0.30 MPa and a normal load of 5000 N. Fig.2 presents the experimental results for the radial tire stiffness and the linear approximation at different air pressures.

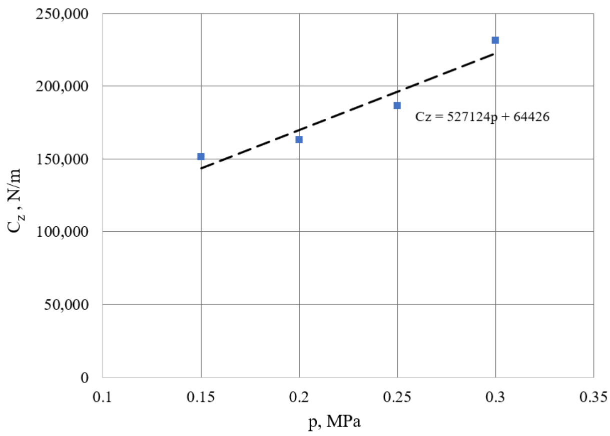


Fig. 2. Experimental results and linear approximation for the static radial stiffness.

Table 1 displays the results of the tire stiffness at air pressures 0.18, 0.20, 0.22, 0.25 MPa, respectively.

Table 1 Radial tire stiffness

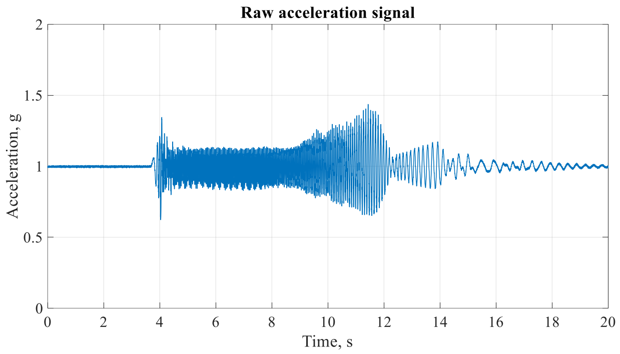
Air pressure, MPa	Tire stiffness, N/m
0.18	159,308
0.20	169,851
0.22	180,393
0.25	196,207

To perform the analysis, it is necessary to distribute the masses of the missing components to the sprung and unsprung parts in the 3D model.

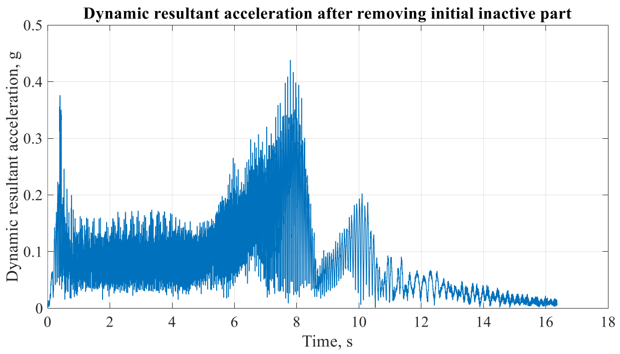
Frequency analysis of the suspension was performed, and three-dimensional blended curvature-based mesh was generated. The mesh includes 346,003 nodes and 212, 369 elements.

B. Methodology of experimental study

The natural frequency of the vehicle body was estimated by frequency-domain analysis of the acceleration signal measured by a triaxial accelerometer mounted near the upper shock absorber attachment point to the vehicle body. The acceleration signals were recorded in the time domain and subsequently processed in MATLAB (Fig.3a). Prior to the frequency analysis, the initial inactive part of the record, corresponding to the time before the shock absorber tester started operating, was removed (Fig.3b). The beginning of the excitation was detected automatically based on the moving RMS value of the dynamic acceleration signal.



a) Raw acceleration signal



b) Dynamic resultant acceleration

Fig. 3. Acceleration signal at tire air pressure 0.22 MPa.

The vertical acceleration component was used for the estimation of the vehicle body frequency, since it is the most representative component for the bounce motion of the sprung mass. The DC component, including the gravitational component, was removed from the signal. A band-pass filter in the frequency range of 0.5–3 Hz was then applied in order to isolate the low-frequency response of the vehicle body from the higher-frequency components associated with the unsprung mass, wheel dynamics, and suspension elements (Fig.4).

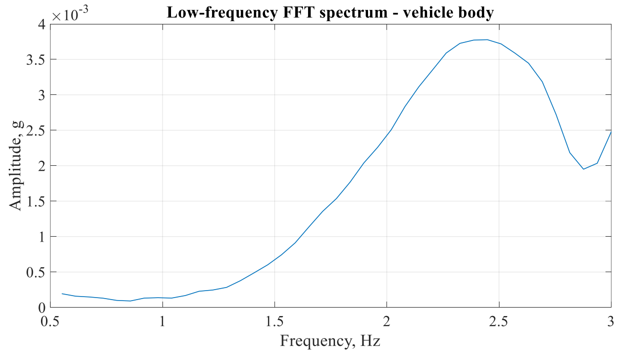


Fig. 4. Low-freauency FFT spectrum at tire air pressure 0.22 MPa.

The frequency spectrum of the filtered signal was obtained using the Fast Fourier Transform. A Hann window was applied to reduce spectral leakage. The natural frequency of the vehicle body was estimated as the frequency corresponding to the dominant peak in the amplitude spectrum within the selected low-frequency range. Therefore, the obtained value should be interpreted as an estimate of the dominant low-frequency dynamic response of the vehicle body at the measurement location.

III. Results and Discussion

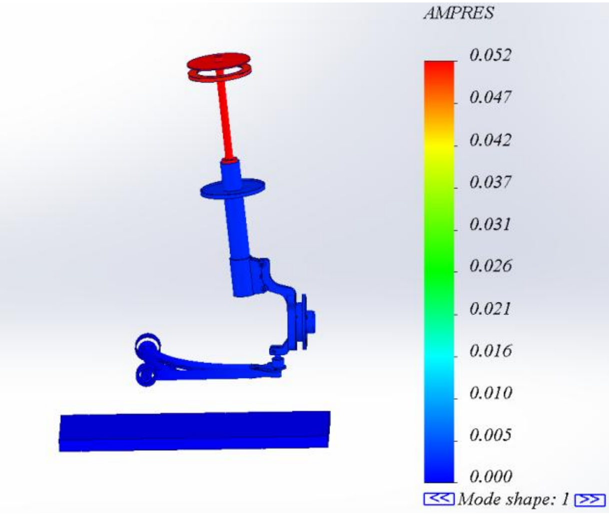
A. FEA frequency results

Table 2 presents the obtained results of the first and second natural frequencies of a quarter MacPherson suspension at different air pressures using polyurethane and rubber bushings of the arm.

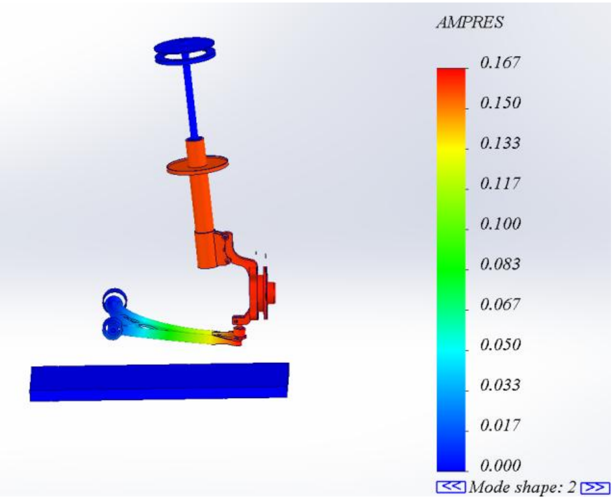
Fig. 5 presents the obtained results of the first and second mode shapes of a quarter MacPherson suspension at tire air pressure 0.22 MPa.

Table 2 Natural Frequency from Fea.

Mode number	Natural Frequency, Hz			
	0.18	0.20	0.22	0.25
First	1.23	1.23	1.24	1.24
Second	14.4	14.6	14.8	15.2



a) first mode shape



b) second mode shape

Fig. 5. Mode shapes.

The results of the first and second natural frequencies are realistic, as their frequency range is from 0 to 20 Hz, which is recommended for uneven road surfaces.

B. FFT frequency results

TABLE 3 NATURAL FREQUENCY FROM FFT.

Mode number	**Natural Frequency, Hz**			
	0.18	0.20	0.22	0.25
First	2.49	2.42	2.38	2.33
Second	11.02	11.12	11.35	11.40

A dominant peak was observed at approximately 2.38 Hz at tire air pressure 0.22 MPa in the low-frequency spectrum. This frequency was considered as an estimate of the vehicle body low-frequency natural response at the upper shock absorber mounting point.

The second natural frequency of 11.35 Hz at tire air pressure 0.22 MPa is more likely related to the dynamics of the unsprung mass, whose vibrations are transmitted to the vehicle body through the shock absorber attachment point.

The variation of tire air pressure in the investigated range did not lead to a significant shift of the first and second identified natural frequencies. The maximum relative variation of the first natural frequency is 0.066 % and of the second natural frequency is 0.034 %.

The results obtained of natural frequencies by FEA are comparable to those obtained FRF analysis.

IV. CONCLUSIONS

Based on the performed study the following conclusions are made:

To validate the FEA model developed of the quarter front MacPherson suspension, was conducted frequency-domain analysis of the acceleration signal, yielding results close to those obtained through FEA. The obtained results indicate that the lowest natural frequency is in the range of 1.24 to 2.4Hz, and is in the frequency range of road surface irregularities (0 to 20 Hz).

The use of experimental data and obtained elastic characteristics of the tire, spring and bushings of previous studies by the authors allows to obtain more realistic results for the natural frequencies and mode shapes using FEA, which more accurately reflect the actual behavior of the suspension.

The developed 3 D model of quarter suspension, along with the study methodology and results, can be used for various types of analysis.

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