

Influence of Rubber Temperature on Transfer Functions of Bushings

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ABSTRACT

In ride comfort as well as driving dynamics, the behavior of the vehicle is affected by several subsystems and their properties. When analyzing the suspension, especially the characteristics of the main spring and damper but also rubber bushings are of main importance. Still, the properties of the different components are dependent on the present operating conditions. Concerning rubber bushings, several effects have already been investigated, e.g. dependencies of the transfer function of frequency, amplitude or load history. In this context influences of changes in temperature are often neglected. However, in the following research, the focus specifically lies on determination and analysis of the temperature dependency of rubber bushings. For this purpose, initially the relationship between properties of pure rubber and rubber bushings is described, which serves as a basis for correlating respective temperature dependencies. Furthermore, bushings of the suspension and power train have been measured using a novel testing method for vehicle bushings incorporating a hydraulic test rig in combination with a heating chamber. Based on the conducted measurements, static as well as dynamic properties of the bushings are presented. In this context, the results are analyzed using the previously presented material properties as well as structural and geometrical aspects of the respective bushing. An outlook on the influence on full vehicle characteristics is given. Based on the presented findings, simulation models of rubber bushings as well as determination of component, subsystem, and full vehicle properties can be improved when temperature dependency is considered.

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INTRODUCTION

Suspension characteristics are dependent on various components. Beside springs, dampers, and components determining kinematic behavior, e.g. levers and joints, elasto-kinematic properties are predominantly defined by characteristics and positioning of rubber bushings. By independently designing their stiffness and damping properties in different directions in space, demands concerning overall vehicle specifications can be met. The application of high stiffness in lateral direction provides a minimal change in camber and trail when side forces are applied while low stiffness in longitudinal direction allows for a high relative displacement of the wheel mount, when obstacles are passed [1]. Therefore forces acting on the body are reduced, resulting in lower longitudinal accelerations, contributing to ride comfort.

However, the characteristics of bushings depend on many properties. In this context static behavior as well as dependency of frequency and amplitude of the response on a dynamic harmonic excitation are commonly examined. Former is evaluated by a static force-displacement curve, as depicted in Figure 1.

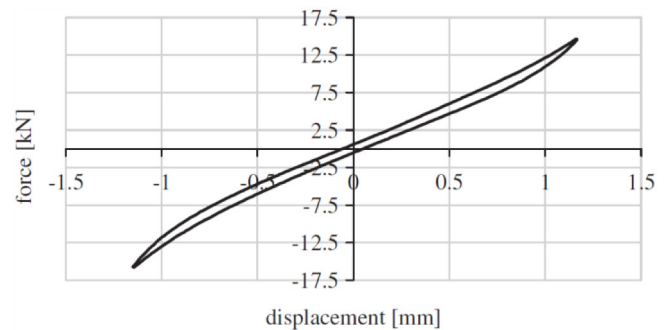


Figure 1. Typical force-displacement curve for a rubber bushing, as depicted in [2]

The static behavior can be characterized by specific properties. The increase of force against displacement is determined by static stiffness. In the linear region of the curve this value is described as constant, while depending on the given bushing, progressive regions can appear where stiffness rises with further deflection. Additionally, the area enclosed by the curve is representative for the amount of static hysteresis or rather dissipated energy, which occurs in one load cycle [3].

On the other hand, dynamic behavior is defined by dynamic stiffness. In this context, magnitude and loss angle of this characteristic value are usually examined. The magnitude corresponds to the quotient of the individual magnitudes of force and displacement while loss angle defines the phase difference between these signals. The characteristic values are depicted in Figure 2.

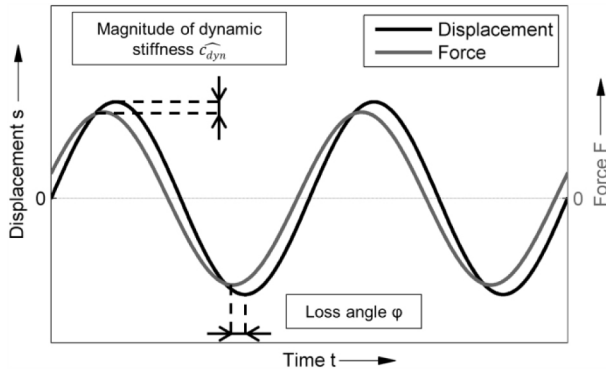


Figure 2. Magnitude and phase angle of the dynamic stiffness

For rubber bushings, dynamic stiffness shows specific dependencies of frequency and amplitude. These will be shown on example of a given bushing, as depicted in Figure 3. In the figure magnitude and loss factor are presented over frequency and amplitude. Hereby, the loss factor corresponds to the tangent of the loss angle.

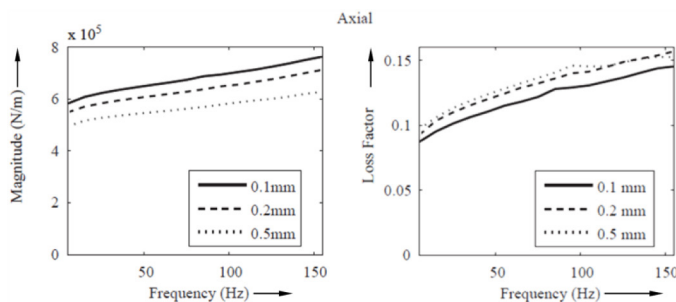


Figure 3. Frequency and amplitude dependency of magnitude and loss factor of the dynamic stiffness, adapted from [4]

As can be seen in the figure, magnitude and loss factor are increasing with frequency. This occurs mainly due to inner damping of the material. On the other hand, the magnitude is falling with rising strain amplitude which is predominantly discussed as Payne-effect [5].

It can be assumed that these transfer characteristics of bushings are dependent of material properties combined with geometrical aspects of the bushing. Therefore the behavior of bushings can be correlated with the behavior of the corresponding material. This is also confirmed by the fact, that the dependencies of dynamic stiffness as well as loss factor in Figure 3 are similar to these of shear modulus, which have been identified for carbon-black filled rubber [4].

Aside from these, material properties are usually characterized by the complex modulus of elasticity E^* , which is determined in a dynamic-mechanical analysis. The parameter is defined by the relation of stress and strain according to (1).

$$E^* = \frac{\sigma_c}{\epsilon_c} = E' + iE'' \quad (1)$$

Hereby, stress and strain are defined by σ_c and ϵ_c resulting in the complex modulus defined by a real and an imaginary part. In this context the real part consists of a storage modulus E' specifying the amount of force generated during steady-state deformation of the material which characterizes elastic properties. On the other hand, the imaginary part is defined by the loss modulus E'' being proportional to the amount of energy dissipated in the material during a load cycle [6]. Additionally, the already described dissipation or loss factor can be calculated by dividing loss and storage modulus, according to (2).

$$\tan \delta = \frac{E''}{E'} \quad (2)$$

The loss factor describes the ratio of energy dissipation and recoverable energy [6].

According to (3) and (4), in case of a cuboid geometry, stress and strain can be directly converted into force and displacement when area A_s and length l are known.

$$\sigma_c = \frac{F}{A_s} \quad (3)$$

$$\epsilon_c = \frac{\Delta l}{l} \quad (4)$$

For complex geometry like rubber bushings, a specific area A_s and length l cannot be defined. Still, a direct correlation between dynamic stiffness of the bushing and elastic modulus of the material is given.

The complex modulus of elasticity E^* can be dependent on several properties. Beside the influence of frequency and amplitude, as already depicted in Figure 3, another parameter affecting this characteristic value is temperature. In Figure 4 the dependency of the complex modulus of elasticity E^* and its components as well as the loss factor against temperature are depicted.

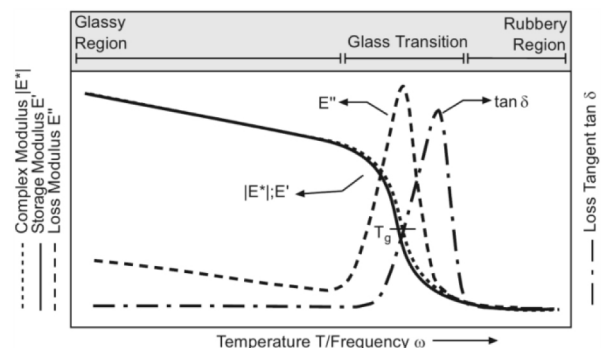


Figure 4. Modulus of elasticity and loss factor against temperature [6]

As can be seen in the figure, storage modulus E' is falling continuously with rising temperature, while in the so-called glass transition area a higher decrease becomes obvious. The Loss modulus E'' is also generally falling except a local maximum occurring in the glass transition area. This maximum correlates to a local maximum of the loss factor $\tan \delta$ at higher temperature, which appears not before the storage modulus E' has become small enough in the corresponding quotient, according to (2).

However, even if these relationships have been identified for different types of elastomers, temperature dependency of rubber bushings still has not yet been fully understood. Therefore, the main focus of this paper is on investigating temperature dependency of bushings with different constructional and material properties in context with a change of transfer characteristics due to changes in frequency or amplitude.

TESTING EQUIPMENT FOR DETERMINATION OF BUSHING PROPERTIES

To measure characteristics of rubber bushings at various temperatures, frequencies and amplitudes, a hydro-pulse test rig is used (see Figure 5). The test rig primarily consists of a hydraulic cylinder (3) and a load cell (2), mounted on a rack (1). Between cylinder and load cell, the investigated bushing (4) is applied via appropriate mountings (5). While performing tests, the rig allows for two different operating modes: displacement-controlled and force-controlled. In former case the cylinder moves until a given displacement is reached and the load cell measures the transmitted force. In the latter case the cylinder moves until a given force value is reached.

For determining influence of temperature changes on bushing characteristics, the test objects are conditioned before defined load cycles are applied. For measuring at lower temperatures, the bushing is cooled overnight to ensure refrigeration across the whole component. Higher temperatures, up to 100°C, are achieved by using a heating chamber (see Figure 5 right, red dot). The heating is regulated by a two-level controller with a hysteresis of $\pm 1^\circ\text{C}$ around a specified temperature.

Since the sensor measures the air temperature inside the chamber, a more precise way to determine the bushing temperature is reasonable. To meet this requirement, a Pt100 resistance thermometer is applied on the surface of the rubber. The thermometer type is Class AA with an error of $\pm(0.1+0.0017|T|)^\circ\text{C}$ (according to [7]). By using a four-wire circuit to connect sensor and transmitter, the cable length does not affect the measured temperature. The transmitter converts the resistance of the thermometer into a proportional voltage and passes the signal to the controller. Compared to thermal elements or the sensor of the air chamber, by the usage of Pt100 sensors it is ensured that a maximum accuracy is achieved, when determining the bushing temperature.

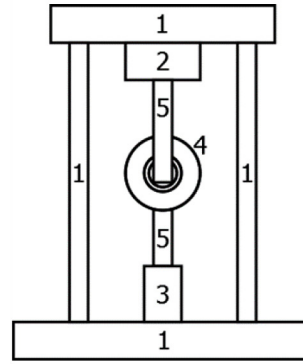


Figure 5. Hydro-pulse test rig - left: 1 rack, 2 load cell, 3 hydraulic cylinder, 4 bushing, 5 mounting / right: photo of test rig with heating chamber (red dot)

Three rubber bushings are chosen as testing objects, each of them with a different location and function inside the passenger car. Two of them are located in the suspension system and one in the engine attachment.

The first suspension bushing is called “U3” and is shown in Figure 6. It is a cylindrical bushing with a length of 65 mm and a diameter of 75 mm. As a constructional feature there are oil-filled cavities, which take effect in X-direction, as indicated in the sketch on the right side of the figure.

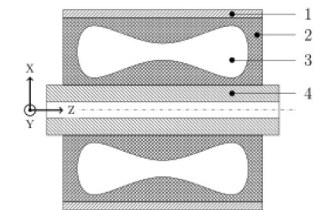
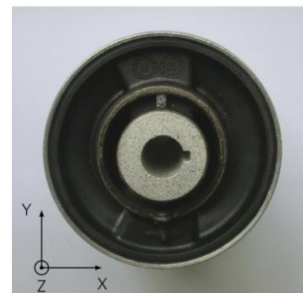


Figure 6. U3-bushing (left) and sketch of oil filled cavities in X-direction (right) with outer cylinder (1), rubber sidewall (2), oil filled cavity (3) and inner cylinder (4)

The second suspension bushing is called “U1” and is shown on the left side of Figure 7. The flexible part of this bushing is made of solid rubber, without oil-filled cavities. In Y-direction less rubber is applied than in X-direction, corresponding to less stiffness in this direction. The bushing is smaller than the U3-bushing, with a length of 35 mm and a diameter of 50 mm.

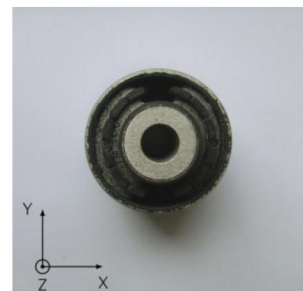


Figure 7. U1-bushing (left) and engine-bushing (right)