

Application Study of Nonlinear Viscoelastic Constitutive Model for Dynamic Behavior of Suspension Arm Bushing

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ABSTRACT

Ride quality is an important purchasing consideration for consumers. It is typically defined in terms of noise, vibration and harshness. These phenomena are a result of vibrations caused at the engine/powertrain and from the road surface, which are transmitted to the passenger cabin. To minimize such vibrations, rubber parts are used extensively at mounting points for the cabin, such as engine mountings and suspension bushings. The vehicle development process increasingly requires performance testing, including rubber parts using CAE, prior to prototype evaluation. This in turn requires a rubber material model that can accurately describe dynamic characteristics of rubber components, particularly frequency and amplitude dependency. Conventional rubber models using commercially available structural analysis solvers cannot solve for both frequency and amplitude dependency at the same time, and are unable to predict transient phenomena such as harshness that involve inputs of varying amplitude. The authors have proposed a new rubber material model that is able to reproduce both frequency and amplitude dependency simultaneously, based on the rubber material model developed by Simo, J.C. [1]. Previous studies have demonstrated the accuracy of the new model under quasi-static and harmonic input conditions. Actual vehicle evaluation involves several input directions, with simultaneous translational and rotational inputs that are transient. In this paper, the new rubber material model is applied to a suspension arm bushing to confirm bushing force when subjected to complex inputs. The model was shown to predict bushing stiffness with greater accuracy and therefore was validated.

CITATION: Ueda, M., Ito, S., and Suzuki, D., "Application Study of Nonlinear Viscoelastic Constitutive Model for Dynamic Behavior of Suspension Arm Bushing," *SAE Int. J. Passeng. Cars - Mech. Syst.* 9(1):2016, doi:10.4271/2016-01-1375.

INTRODUCTION

Ride quality in a vehicle is expressed in terms of factors that directly affect the occupants, such as vibration, noise and harshness (unpleasant sensations such as jolting). Ride quality is therefore considered a key selling point in terms of vehicle performance. Vibration is transmitted from the engine and powertrain as well as the road surface to the vehicle cabin, and thence to the occupants. In order to minimize the level of vibration reaching the cabin, rubber parts such as engine mounts and suspension bushings are deployed extensively in components used to join the engine and suspension systems to the cabin.

Given that rubber parts used in the joint portions between components have a significant bearing on ride quality, the vehicle development process will ideally include a CAE analysis of ride quality including rubber parts to provide a preliminary evaluation of ride quality prior to the prototype testing stage. This analysis requires a rubber material model that can accurately reproduce the dynamic characteristics of the rubber parts, particularly with respect to frequency and amplitude dependency. However, conventional rubber material models that use commercially available structural analysis solvers cannot reproduce both frequency and amplitude dependency

at the same time. This makes it difficult to generate accurate predictions of transient phenomena such as harshness, where the amplitude is constantly changing.

The authors have developed a rubber material model [2] (hereafter denoted the "new rubber material model") based on the nonlinear viscoelastic rubber model proposed by Simo, J.C. [1] that is capable of reproducing both amplitude and frequency dependency at the same time. The accuracy of the new rubber material model has been demonstrated in both quasi-static condition and harmonic oscillation condition. [2]

Bushing components in an actual vehicle are generally subject to simultaneous and transient inputs in the translational as well as rotational directions. It is rare that an input is confined to a specific frequency in a uniaxial direction. At SAE, Hartley, C. et al. (2012) [3] and Nakahara, J. et al. (2015) [4] have previously described methods that are capable of reproducing both frequency and amplitude dependency at the same time. However these studies tend to concentrate on bushing force generated by inputs in the uniaxial direction. There is no literature on bushing force for multi-axial inputs or transient inputs.

This study reports on the reproducibility of bushing forces associated with multi-axial inputs and transient inputs in the new rubber material model applied to bushing components in a suspension arm as shown in [Figure 1](#). The ultimate aim is to improve the accuracy of harshness analysis using the vehicle model.

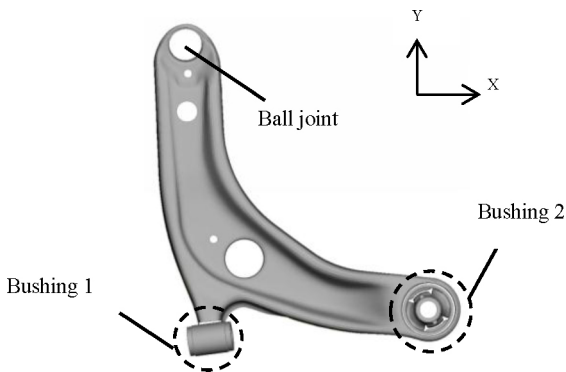


Figure 1. Suspension arm model

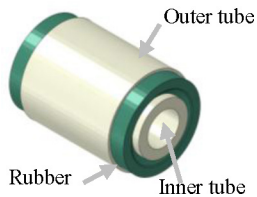


Figure 2. Bushing 1 model

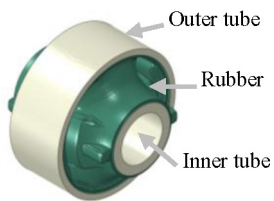


Figure 3. Bushing 2 model

RUBBER MATERIAL MODEL

Basic Concept of the New Rubber Material Model

[Figure 4](#) illustrates the concept of the rubber material model proposed by Simo, J.C. [1], while [Equation 1](#) shows the associated equation of evolution for stress and strain.

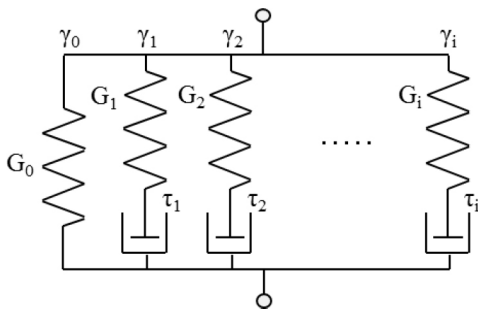


Figure 4. Representation of constitutive law for rubber material

$$\frac{dQ_i}{dt} + \frac{Q_i}{\tau_i} = \frac{\gamma_i}{\tau_i} DEV \left[\frac{2\partial \bar{W}^0(\bar{C})}{\partial \bar{C}} \right]$$

Equation 1

where

G_i is the modulus of elasticity for the network

γ_i is the modulus ratio for the network

τ_i is relaxation time

Q_i is stress-like internal variable

$\bar{W}^0$ denotes the deviatoric parts of the initial elastic stored energy

$\bar{C}$ denotes the deviatoric part of the right Cauchy-Green deformation tensor

The new rubber material model describes amplitude dependency by defining relaxation time τ_i in [Equation 2](#) as follows:

$$\tau_i = \frac{1}{A_i} |\bar{E}'|^{m_i}$$

Equation 2

where

$\bar{E}'$ is a norm of the strain rate tensor

$A_i m_i$ are material coefficients

Note that these must be identified along with G_i and γ_i in [Figure 4](#). Identification of material coefficients is described below.

Identification of Material Coefficients

The network material coefficients were determined from the experimental observations using the test pieces of the material used in the bushing components. [Figure 5](#) shows a sample procedure for calculating the material coefficients.

The hyperelastic portion corresponding to G_0 was modeled with the Yeoh model [5] [6]. In the Yeoh model, the strain energy per unit of reference volume (the elastic potential that indicates strain energy per unit volume) is expressed as shown in [Equation 3](#).

$$U = \sum_{i=1}^3 C_{i0} (\bar{I}_1 - 3)^i + \sum_{i=1}^3 \frac{1}{D_i} (J_{el} - 1)^{2i}$$

Equation 3

where

$\bar{I}_1$ is the first deviatoric strain invariant

J_{el} is the elastic volume ratio

In the Yeoh model, the coefficients of elastic behavior C_{10} , C_{20} and C_{30} are determined from the uniaxial tensile test results, while the coefficient for volumetric change D_1 assumes linear volumetric change and is defined for D_1 only. The G_0 value is used for G_1 through G_i . Next, the results from the harmonic oscillation test were used to determine the values of m_i and A_i . The proportion of γ_i in each network was determined via optimization with the storage modulus and loss modulus from the harmonic oscillation test as the objective function. Table 1 lists the resulting material coefficients.

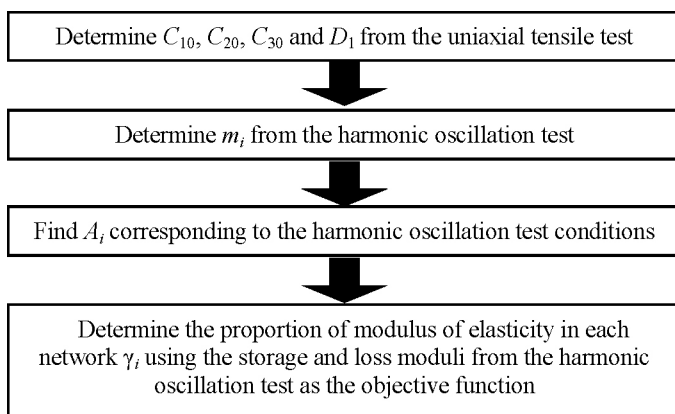


Figure 5. Calculating the material coefficients

Table 1. The material coefficients

	Bushing 1				Bushing 2			
	C1	C2	C3	D1	C1	C2	C3	D1
Hyperelasticity parameters	5.4413	-0.6388	0.2475	0.01	4.403	-0.014	0.269	0.01
Viscoelasticity parameters	Network No.	Ai	γi	mi	Network No.	Ai	γi	mi
	0	—	0.1000	0.897	0	—	0.1000	0.790
	1	10	0.0989		1	10	0.1795	
	2	100	0.0743		2	100	0.1857	
	3	10000	0.3525		3	500	0.2865	
	4	50000	0.3744		4	50000	0.2483	

Validation of Material Coefficients

This section concerns validation of material coefficients derived as per the procedure detailed above. We used the Abaqus [6] 6-14.1 solver for calculation, and figure 6 shows the single-element validation model used to define the material coefficients thus obtained.

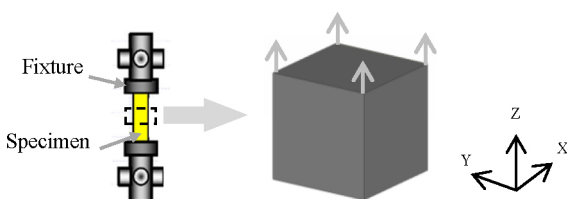


Figure 6. Material test piece model

The first validation was of the quasi-static uniaxial tensile test characteristics. This involved comparing the stress-strain calculations with the corresponding experimental observations, as illustrated in Figure 7 (bushing 1) and Figure 8 (bushing 2). From Figures 7 and 8, it can be seen that the calculation results accurately represent the quasi-static uniaxial tensile strength characteristics.

The next validation was of harmonic oscillation characteristics. The validation model was the same as in Figure 6, with the dynamic modulus as the performance index. Figures 9 and 10 compare calculated values with experimental data for materials of bushings 1 and 2 respectively. It can be seen that the two sets of values diverge by up to around 10% for the material of bushing 1, but are largely reproducible for the material of bushing 1 and bushing 2. Amplitude dependency, meanwhile, is reproducible for both materials, and this demonstrates the validity of the new rubber material model.

Thus it was concluded that the material coefficients determined above faithfully reproduce the quasi-static characteristics and harmonic oscillation characteristics.

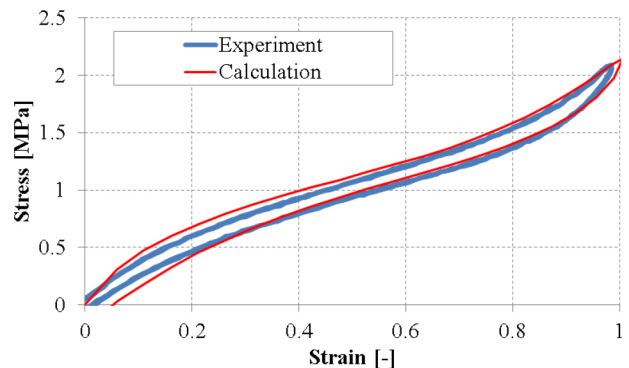


Figure7. Quasi-static stress-strain curve for the material of bushing 1

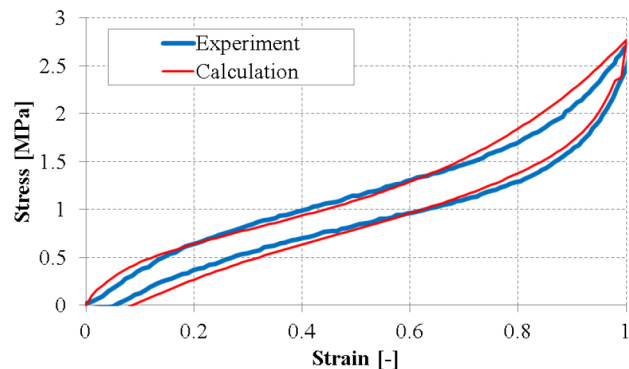


Figure 8. Quasi-static stress-strain curve for the material of bushing 2