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A nonlinear constitutive model by spring, fractional derivative and modified bounding surface model to represent the amplitude, frequency and the magnetic dependency for Magneto-sensitive rubber

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ABSTRACT

Magneto-sensitive (MS) rubber is a kind of smart material mainly consisting of magnetizable particles and rubber. Inspired by experimental observation that the shear modulus for MS rubber is strongly dependent on amplitude, frequency and magnetic field; while the impact for the magnetic field and strain to the loss factor is relatively small, a new nonlinear constitutive model for MS rubber is presented. It consists of a fractional viscoelastic model, an elastic model and a bounding surface model with parameters sensitive to the magnetic field. To our knowledge, it is the first time that the bounding surface model is incorporated with the magnetic sensitivity and used to predict the mechanical properties for MS rubber. After comparison with the measurement results, it is found that the shear modulus and the loss factor derived from the simulation fit well with the experimental data. This new constitutive model with only eight parameters can be utilized to describe the amplitude, frequency and the magnetic field dependence for MS rubber. It provides a possible new way to understand the mechanical behavior for MS rubber. More importantly, the constitutive model with an accurate prediction property for the dynamic performance of MS rubber is of interest for MS rubber applications in noise and vibration reduction area.

1. Introduction

Vibration is a common phenomenon in the world. For example, vibration exists in mechanical devices under operating and it occurs when structures are subjected to dynamic external loadings. In most cases, vibration is unwanted because it reduces the working life of machine, wastes energy and may cause noise. One commonly used way to reduce vibration is to install some vibration isolators for the target objects. Generally, vibration isolators are made of rubber, which means that the dynamic properties of vibration isolators is fixed once mounted. Therefore, it is impossible to change its characteristics to adapt to various excitation conditions. In that case, when the frequency for the excitation is close to the critical frequency for the system, the vibration attenuation effect of the vibration isolators would be greatly reduced and can even collapse because of frequency mis-tuning problems.

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However, magneto sensitive (MS) rubber, a kind of smart material, may find a solution for the mis-tuning problem. It mainly consists of polarized iron particles embedded in a rubber matrix. Under a magnetic field, the mechanical characteristic of MS rubber can be modified rapidly, reversibly and continuously. MS rubber is categorized into either anisotropic or isotropic according to the presence or absence of the magnetic field in the vulcanization process. If MS rubber is used for the fabrication of vibration isolators, an increased vibration reduction effect may be obtained by the stiffness changing capacity of MS rubber.

Research on MS rubber started in the late 1990s by Jolly et al. [1] and Ginder et al. [2]. For the last two decades, more researchers have begun the study on MS rubber. The research on MS rubber can be mainly divided into four categories; those are: fabrication, testing, application and modeling. For the fabrication of MS rubber, a wide range of methods aimed at obtaining MS rubber with high MS effect are used. By finite element modeling, Davis [3] predicted that the optimum particle volume fraction for MS rubber to obtain the largest change in modulus is 27%. The result was then verified experimentally [4]. For anisotropic MS rubber, the effects of matrix [5], coupling agent, content of iron particles, plasticizers [6] pre-structure [7] and surfactant [8] on the MR effect were considered. Muniain et al. [9] studied the influence of carbon black and plasticizers on the dynamic properties of isotropic MS natural rubber. Recently, Stanier and his coworkers [10] chose a new method for the fabrication of MS rubber. In their study, nickel-coated carbon fiber was embedded in elastomer and a magnetic field is applied during the vulcanization to obtain a transversely isotropic composite. Subsequently, they investigated the effect of the orientation of the nickel-coated fiber to the magneto mechanical behavior of MS rubber.

For the testing of the mechanical properties for MS rubber, the influence of the magnetic field, frequency and temperature on the dynamic stiffness [11,12] and the loss factor [13] of isotropic MS rubber have been studied. In parallel, large efforts have been made to investigate the impact of magnetic field, frequency [14], temperature [15] on the viscoelastic properties of anisotropic MS rubber. Among all the investigations related to testing of MS rubber, Blom and Kari [16] investigated the Fletcher Gent effect [17] of the isotropic MS rubber in a wide frequency range and it revealed that in addition to viscoelastic properties, there is a strong amplitude dependency of MS rubber even for a small strain.

The magnetic field sensitivity property of MS rubber makes it attractive for the potential application in semi-active vibration control field. For example, Deng and Gong [18] designed a MS rubber based dynamic vibration absorber. The research result revealed that the adaptively tuned vibration absorber comprised of MS rubber is efficient for tracking the excitation frequency and reducing the vibration of the primary structure. Jung et al. [19] fabricated a base isolation system of MS rubber and installed it on a scaled building structure to investigate the seismic performance of that smart base isolation system. The result showed that compared with conventional base isolation systems, the base isolation system made of MS rubber outperforms in reducing the vibration of the building structure. Similar research was done [20–22] suggesting the feasibility of using MS rubber for improving the vibration attenuation effect and staggering the natural frequency of structure from the loading frequency. Other application of MS rubber in vibration control area includes exploring the potential of using adaptive sandwich beams filled with MS rubber to reduce the vibration of vibrating structural elements like helicopter blades and aircraft wings. For instance, Nayak et al. [23] proposed the governing equation for free vibration of a sandwich beam filled with MS rubber under various boundary conditions. Aguib et al. [24] discussed the effect of different magnetic fields and different percentage of ferromagnetic particles on the vibration response of MS rubber sandwich plates. Furthermore, Dyniewice et al. [25] validated the feasibility of reducing the vibration of a sandwich beam partially filled with MS rubber by changing the magnetic field.

There are a number of models developed for the magnetic related mechanical properties of anisotropic MS rubber. Primarily, Jolly et al. [1] proposed a dipole model to represent the magnetic related mechanical properties of the anisotropic MS rubber. Later, Zhu et al. [26] augmented that model by considering the influence of adjacent chains. Dorfmann and Ogden [27–29] derived the governing equations for the deformation of MS rubber by combing Maxwell equations with continuum mechanics and Itskov et al. [30] then extended the model by introducing the mathematically poly-convexity notion. Unfortunately, those models are only valid for the quasi-static case due to the neglect of the viscoelastic effects for MS rubber. To model the viscoelastic behavior of anisotropicMS rubber, a Bouc-Wen and a Kelvin-Voigt model were aligned in parallel to represent the viscoelastic behavior of MS rubber [19]. The main drawback of that model is the high computational cost for identifying the material parameters. To solve that problem, a modified Kelvin-Voigt model for which the parameters in stiffness and damping element are all related to the magnetic field, frequency and strain were proposed [31]. However, the agreement between the simulation and experiment result for the loss factor needs to be improved. More importantly, for all the models mentioned above, the measurements are performed based on the anisotropic MS rubber where the iron particles are aligned in chains. For isotropic MS rubber, the distribution of iron particles and the mechanical behavior are completely different. Based on that physical fact, Rudykh et al. [32,33] investigated the effect for distribution of magnetizable particles on the magneto-mechanical coupling effect and stability for MS rubber. The Fletcher-Gent effect, which represents the dependence of the modulus on the amplitude of the applied strain for MS rubber was generally omitted for the model mentioned above. However, according to the research by Blom and Kari [16], the amplitude dependent stiffness behavior is an important feature for MS rubber and should not be ignored. To describe the dynamic behavior of MS rubber completely, a model which incorporated the Fletcher-Gent effect for MS rubber is needed. In 2011, a nonlinear constitutive model that includes the effect of strain, frequency and magnetic field for the mechanical behavior for isotropic MS rubber was proposed by Blom and Kari [34]. In their model, a fractional derivative was used to describe the viscoelastic properties and a smooth frictional stress model was adopted to describe the Fletcher-Gent effect for MS rubber.

In fact, there are other methods that are capable of capturing the Fletcher-Gent effect for filled rubber. One possible way is to use the bounding surface model, which was proposed by Dafalias and Popov [35] in 1977. The innovation of the bounding surface model is that the plastic modulus could vary continuously and the specialized case for bounding surface model could be