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Dynamic performance of a multi-ribbed belt based on an overlay constitutive model of carbon-black-filled rubber and experimental validation

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ABSTRACT

The focus of this work is the accurate prediction of dynamic mechanical performances of a multi-ribbed belt span. An overlay constitutive model, which consists of hyperelastic, viscoelastic and elastoplastic parts coupled in parallel, is established to describe mechanical properties of carbon-black-filled rubber material used in the belt. A uniaxial tensile test and a uniaxial compressional test are conducted to obtain the hyperelastic material parameters of the constitutive model, and a simple dynamic shear test is used to identify the viscoplastic material parameters via a standard genetic algorithm. Finite element (FE) simulations with the constitutive model are performed to simulate static and hysteretic dynamic characteristics of rubber specimens in these tests. By comparing the simulation results with experiments, the accuracy of the constitutive model and its material parameters is validated. A three-dimensional FE model based on the constitutive model is established to predict both longitudinal and transverse dynamic performances of the multi-ribbed belt span and its good agreements with experimental results are achieved.

1. Introduction

Due to advantages of low price, vibration damping, noise reduction and so on, filled rubber material is widely employed in engineering applications such as belt drive systems. As one kind of the belt drive systems, an automotive accessory belt drive system usually uses a multi-ribbed belt to power all accessories such as an air conditioner, water pump, alternator and power steering pump as shown in Fig. 1. Noise, vibration and harshness (NVH) behaviors of the automotive accessory belt drive system are mainly determined by dynamic characteristics of the belt. Hence, the premise for exactly predicting the NVH behaviors of the automotive accessory belt drive system is to find a method to accurately describe mechanical characteristics of the belt. Once the belt dynamic characteristics are accurately modeled, the dynamic response of an automotive accessory belt drive system in different operational conditions can be exactly predicted. And based on the prediction, optimal design on the automotive belt drive system can be conducted to improve its NVH performance by reducing belt vibrations. The belt early fatigue will of course be improved once the belt vibration is reduced.

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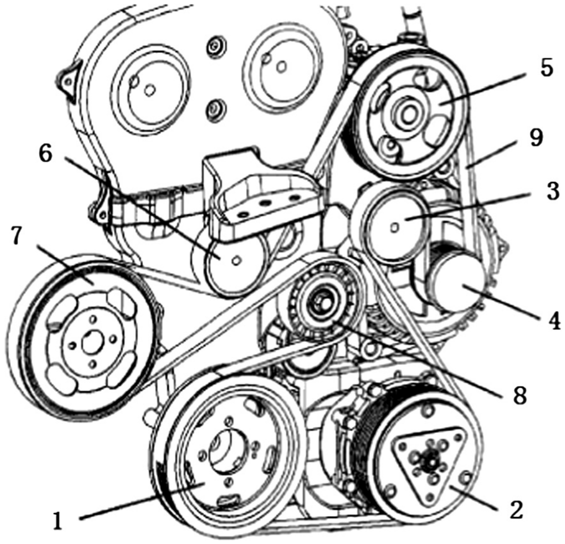

Fig. 1. A typical automotive accessory drive system of engine: 1-crankshaft pulley, 2-air conditioner pulley, 3-idler 1, 4-alternator pulley, 5-power steering pulley, 6-idler 2, 7-water pump pulley, 8-tensioner and 9-multi-ribbed belt.

The main difficulty for modeling a plain belt, v-belt, multi-ribbed belt and so on arises from nonlinearity of filled rubber used in the belt and its composite nature of materials. Rubber materials including both unfilled and filled ones demonstrate obviously nonlinearly elastic behavior under static stretch deformations that is usually called a hyperelastic characteristic. Furthermore, due to fillers added, filled rubber becomes strain-dependent due to Mullins [1] and Payne [2] effects that can be interpreted as the effect of internal filler friction or breakdown and reforming of filler structures. The significance and influence of the two effects depend on both the type of rubber material and loading conditions in engineering applications [3]. There are various hyperelastic models [4] that are employed to predict the hyperelastic behavior of rubber components. Viscoelastic models including classical ones such as Kelvin-Voigt [5–7], Maxwell [6,8,9] and standard linear solid [10,11] models and those that involve fractional partial derivatives [12,13] can describe the performance of either natural or low-filler-reinforced rubber. However, the amplitude dependence, which can be of great importance if the material is heavily carbon-filled to obtain higher modulus, hardness, damping, and so on, cannot be described by these viscoelastic models only. The amplitude-dependent effect is often considered as plastic behavior [14] and results from inconvertible slip processes between fillers [15]. To account for this, In 1998, Berg [16] proposed a more efficient friction model, which was used by Sjöberg and Kari [9,17] to predict isolation properties of rubber isolators; it demonstrated smoother fitting curves than the perfectly plastic model and had less parameters to be determined. However, as it is formulated to relate the force and displacement for a uniaxial deformation case, Berg's model has a problem when it is adopted for a multi-axial deformation case; it can be solved by reformulating Berg's model relating the stress and strain but generic finite element (FE) codes cannot be implemented at once [18]. Austrell [19] and Gregory [20] employed several perfectly plastic elements (bilinear models) coupled in parallel, which form a multi-linear model, to describe the amplitude-dependent effect and obtained excellent results. The perfectly plastic elements use Von Mises elastoplasticity that already exists in FE programs; thus implementation of the plastic part is simplified [18].

Much research [21–27] has been conducted on dynamic responses of belt drive systems. However, few researchers take full consideration of the hyperelastic, viscoelastic and elastoplastic properties of the filler rubber material contained in the belt at the same time. The nonlinear belt stiffness and damping are usually neglected [21,22,27] or linearized [23,25], which will result in some disagreements between the numerical and experimental results. FE simulation [28,29] with an accurate constitutive model of filled rubber is a good way to solve the problem and thus can be used to accurately predict dynamic mechanical performances of belts. These research backgrounds mentioned above motivate this work.

The aim of this work is to present a FE methodology to accurately predict complicated dynamic mechanical performances of a multi-ribbed belt with a 40 deg wedge angle and six ribs. The configuration of the cross section of the multi-ribbed belt is shown in Fig. 2. The multi-ribbed belt is made up of reinforcing cords to carry the tension, cushion rubber to envelope the cords and rib rubber to form belt ribs as seen in Fig. 2. The paper is organized as follows. In Section 2, a constitutive model is established in a general purpose to model a carbon-black (CB)-filled rubber material SHA70 used in the multi-ribbed belt based on the concept of Austrell [3,19]. The constitutive model is actually an overlay model that mechanical characteristics of rubber are decomposed into hyperelastic, viscoelastic and elastoplastic parts coupled in parallel. Section 3 presents the method and process of material parameters identification of the constitutive model: a uniaxial tensile test and a compression test are conducted to identify the hyperelastic material parameters while a simple dynamic shear test is conducted to identify the viscoelastic and elastoplastic material parameters via the standard genetic algorithm (SGA) [30]. Several techniques