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A novel air spring dynamic model with pneumatic thermodynamics, effective friction and viscoelastic damping ☆

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ABSTRACT

An accurate air spring model is critical for vehicle design equipped with air spring pneumatic systems to provide a better performance. However, it is particularly difficult to establish a generalized analytical model to predict the amplitude- and frequency-dependent behaviors of an air spring resulting from many factors such as thermodynamics, friction, and damping. In this paper, an air spring dynamic model is developed by considering the thermodynamics of the bellow-pipe-tank pneumatic system, the effective friction, and viscoelastic damping of the bellow rubber. It is worth mentioning that parameters in the friction model depend on the standard deviation of the displacement excitation through a statistics method rather than constant values in the classic Berg's friction model. The bellow rubber viscoelastic property is modeled by a fractional calculus element with only two parameters. The proposed model parameters are identified and further validated by conducting bench tests of the stand-alone air spring component and the bellow-pipe-tank system, separately. Several models for the air spring are compared with the proposed model and the measurements in harmonic excitations with different amplitudes and frequencies, and random excitations with both large and small displacement cases. The results of comparison show that the proposed model can accurately predict the dynamic characteristics of the air spring in an acceptable computation time.

1. Introduction

The driver/passengers of the vehicle are exposed to the vibrations arising from the vehicle's interactions with the rough roads. Numerous efforts have been devoted to explore the optimized design for various vibration isolation systems in the vehicle to attenuate the harmful vibration and improve the ride comfort [1–5]. As an important vibration isolator, the air spring has been widely applied in the suspension systems of the railway vehicles [6] and commercial vehicles [7–10] due to its significant advantages of low vibration transmissibility coefficient and adaptive load capacity ability. An air spring pneumatic system exhibits strong amplitude- and frequency-dependent dynamic characteristics and its dynamic characteristics are effected by the geometry structures of the pneumatic elements [11,12]. As the air spring pneumatic system

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has significant effect on the ride comfort and driving stability of the full vehicle, it is worth establishing an analytical air spring model which can reproduce the dynamic behavior accurately for vehicle evaluation and design in practical applications.

The air spring bellow is generally used by connecting the auxiliary tank via a pipe to soften the air spring, and this bellow-pipe-tank system can be described by lumped parameter models and thermodynamic models in literatures.

Naoteru and Nishimura [13] proposed a simple mechanical model of the self-damped air spring. However, the Nishimura model results in a large discrepancy when the pipe is long [14]. This shortcoming is overcome in Vampire model [15] by considering the inertial effect of the air mass when moving through the pipe. Berg [16] further developed an air spring model by considering the effect of bellow rubber friction and suggesting that the air damping in the pipe is proportional to the velocity exponent with a value of about 1.8. However, the identified parameters in the model are only applicable for the current preload.

Some thermodynamic models [17–24] have also been developed in recent years. Quaglia and Sorli [21] presented a dimensionless air spring model and the design procedure for a pneumatic suspension. Chang et al. [22] and Lee [23] considered the heat transfer between the internal air and the atmosphere. Docquier et al. [24] compared different air spring models with the pipe modeled using differential and algebraic methods, and suggested an application-dependent choice. Asami et al. [25] reported that the bellow rubber friction was approximately in logarithm relationship with excitation amplitude, and the rubber viscoelastic force was approximately in exponential relationship with excitation frequency based on the experimental results. However, it is difficult for these mathematical relationships to predict the output force when the air spring is subject to a random excitation.

This paper aims to develop a generic air spring model that considers not only the contribution from pneumatic thermodynamics, but also frictional and viscoelastic effects of the bellow rubber. In this proposed model, friction model parameters are identified through the standard deviation of the displacement excitation with a statistical method by maintaining Berg's smooth friction model philosophy [26,27]. The excited process is assumed as ergodic and this proposed friction model can adapt to different displacement levels of the excitations. The bellow rubber viscoelastic property is described as a fractional derivative model with only two parameters. Several air spring models are compared with the proposed model and the measurements in both harmonic and random displacement excitation cases to validate the proposed model.

This paper is organized as follows: In Section 2, a generic air spring model is proposed which consists of pneumatic thermodynamics, bellow rubber friction and viscoelastic elements. In Section 3, bench tests of the stand-alone air spring component and the bellow-pipe-tank system are conducted separately to investigate the air spring's characteristics in the quasi-static, harmonic and random excitation conditions. In Section 4, the model parameters are identified through experimental data. In Section 5, the proposed model is validated by comparing it to different air spring models and the experimental measurements in different excitation cases.

2. Model development

In this section, we focus on the vertical (axial) behaviors of the air spring, without considering the effects of bellow rubber's elasticity and heat transfer in thermodynamic process. The total output force of the air spring is the combined results of the thermodynamic force of the pneumatic system, the bellow rubber friction and viscoelastic force under the displacement excitation. The air spring model development is based on these three parts and explained in detail in the following sections.

2.1. Pneumatic system model

As shown in Fig. 1, the air spring, composed of the cover plate, bellow, and piston, connects with an auxiliary tank via a pipe. When the displacement excitation x (m), where x is a function of time t, is applied to the air spring, the air moves

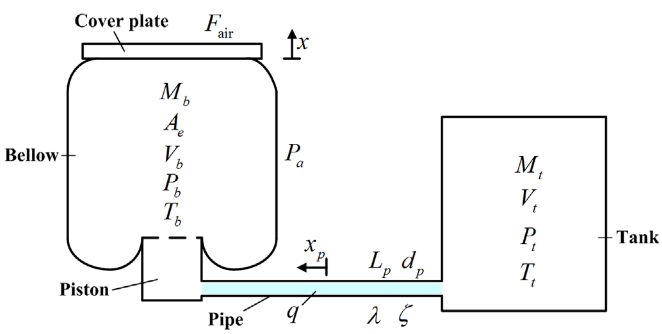

Fig. 1. The bellow-pipe-tank pneumatic system.