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Full Length Article

A combined nonlinear and hysteresis model of shock absorber for quarter car simulation on the basis of experimental data

Vijay Barethiye, G. Pohit *, A. Mitra

Department of Mechanical Engineering, Jadavpur University, Kolkata 700032, India

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ABSTRACT

Modeling dynamic characteristics of an automotive shock absorber is a challenging task due to its complex behavior. In the present paper, the nonparametric and hybrid approach is proposed to represent the nonlinear and hysteresis characteristics of the shock absorber. An experiment is carried out on a car damper utilizing INSTRON to obtain force-velocity characteristics of the shock absorber. The experimental data is used to devise two different models, namely, piecewise linear model and hysteresis model, to capture the damping properties of the absorber and for consequent use in simulations. The complexity involved due to certain physical phenomenon such as oil compressibility, gas entrapment etc. gives rise to hysteresis behavior and the present paper tries to model such behavior with the help of Neural Networks. Finally, a combined (hybrid) shock absorber model (including the characteristics of both piecewise linear and hysteresis behavior) is developed in Simulink and integrated into a quarter car simulation to verify its feasibility. The results generated by the combined (hybrid) model are compared with linear as well as piecewise linear model and the comparison shows that the proposed model substantially a better option to study the vehicle characteristics more accurately and precisely.

1. Introduction

The automotive suspension system has been a focus of attention to researchers over a long period of time as it enhances vehicle stability, handling properties and comfort to the passengers. Due to its multi-dimensional functions, it is regarded as one of the most important item so far as the design of a vehicle is concerned. Since the passenger cars have been historically one of the primary methods of ground transportation [1], it is essential to have a very good vehicle suspension system that can reduce vibration of the chassis to a great extent without compromising vehicle handling quality. Suspension consists of the system of springs, shock absorbers and linkages that connects a vehicle to its wheels. The main function of vehicle suspension system is to support the vehicle body and provides riding comfort [2–3].

A shock absorber is the key element of the suspension system. It is used to dissipate energy and hence reduce vertical oscillation of the vehicle arising out of unevenness of the road surface. Comfort and road-handling performance of a vehicle are mainly determined by the damping characteristic of the shock absorbers [4]. The shock absorbers generally used in motorcycle, car, light and heavy vehicle exhibit the nonlinear and complex behavior [5–9]. The shock absorber is typically characterized by the force-velocity curve also called characteristics diagram. The modeling of the force-velocity characteristics curve is not a trivial task due to the presence of hysteresis loop and nonlinear behavior of the damper [10]. The absorber damping force is not only a strongly nonlinear function of piston velocity but also exhibits asymmetric behavior in compression and rebound region.

In recent time, extensive researches have been carried out to determine characteristics of the shock absorber. From the literature, it shows that the development era towards the modeling can be categorized as theoretical modeling of physical system [11–18], nonparametric modeling based on algebraic equations [19–23], empirical modeling using various optimizations techniques such as empirical, Neuro-fuzzy [24–27], and hybrid modeling comprising of theoretical-empirical and/or nonparametric-empirical methods [28–34]. Several experiments have been carried out to capture the dynamic properties of shock absorber including its unsymmetrical hysteresis behavior.

Segel and Lang [11] developed the physical damper model having a large number of parameters. However, it is not suitable for dynamic simulation of vehicle performances due to its complex nature. Wallaschek [12] suggested mathematical model using data

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* Corresponding author.

E-mail address: goutam.pohit@jadavpuruniversity.in (G. Pohit).

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Nomenclature

Symbol description

C_{r1}, C_{r2}, C_{r3}	damping coefficient for rebound (Ns/m)
C_{c1}, C_{c2}	damping coefficient for compression (Ns/m)
f	damping force (N)
v	velocity of piston rod (m/s)
X_n	normalized data (hysteresis force)
X_m	measured values (hysteresis force) from experimental data
m_s	sprung mass for quarter car vehicle (kg)
m_u	unsprung mass for quarter car vehicle (kg)
x_s	displacement variables of sprung (m)
x_u	displacement variables of unsprung mass (m)
k_s	suspension system has stiffness (N/m)
k_t	stiffness of the tire (KN/m)
f_d	damper force (N)

obtained from the experiment. He observed that a simple mathematical model with a minimum number of parameters is not good enough to capture the properties of the shock absorber. Besinger et al. [13] developed semi-empirical damper model in which nonlinear spring is attached with the damper in series to describe the nonlinear and hysteretic properties of the shock absorber. Duym et al. [14] highlighted that two-slope or three-slope model of shock absorber exhibited better result compared to the linear model.

In order to capture the complex behavior of shock absorber, Liu and Zhang [19] developed a virtual prototype of a hydraulic shock absorber in ADAMS environment. In the non-parametric category of modeling, Calvo et al. [20], Yan Cui et al. [21] and Siradj [22] developed models using mathematical formulation to describe the nonlinear behavior of shock absorber. Gao et al. [26] developed the strut model using a black-box model technique whereas Beghi et al. [28] proposed the grey-box modeling technique for motorcycle shock absorber; both techniques used artificial neural network approach for the modeling purpose. Lion and Loose [29], and Prancy et al. [30] developed a thermo-mechanically coupled shock absorber model by considering heating phenomenon. Prancy et al. [30] and Cui et al. [21] developed hybrid shock absorber model in which the properties of shock absorber were represented by a spline and polynomial algebraic function followed by neural network technique. Castellani et al. [33] developed the hybrid model of mono-tube shock absorber using physical and empirical modeling. In order to investigate dynamic characteristics of the automotive shock absorber, researchers [34–44] performed experiment along with modeling and analysis.

Calvo et al. [20] analyzed the dynamic behavior of a shock absorber using damper test rig at different frequencies (0.25 Hz, 0.5 Hz, 1 Hz and 3 Hz). By using experimental results, author generated a piecewise bilinear model but did not consider the hysteretic behavior of the damper. Lang [6] studied the frequency dependent behavior of shock absorber. The hysteretic loop in the force-velocity plot was supposed to be due to the compressibility of oil and the presence of either gas or vapor phase at certain stages of the cycle [11,19].

From the literature, it has been observed that various linear and non-linear models have been proposed by different researchers to model force-velocity and force-displacement relationships of the shock absorber. However, little attempts have been made to capture the hysteretic property of shock absorber represented by the area of the curve, as it is difficult to model it through parametric modeling so that prediction of dynamic performance characteristics of a vehicle using the model will be precise.

In this paper, an experiment is carried out on a commercial car damper using INSTRON 8801 servohydraulic testing machine. With the help of frequency and amplitude variation on the damper and sinusoidal excitation, the force-displacement and force-velocity characteristics curves are determined and presented in the paper. The main aim of the work is, to build up the nonlinear and hysteresis characteristics of the absorber. Therefore, in order to construct the actual force-velocity characteristic curve, a combined (hybrid) shock absorber model is developed that can represent the hysteresis and nonlinear characteristics of the shock absorber. Nonlinear properties of the absorber are modeled using the piecewise linear curve, whereas hysteresis effect of the shock absorber is captured by applying Neural Network technique. The model is purely based on force-velocity characteristics phenomenon. The individuality of the work is, modeled both properties successfully in Simulink and incorporated the developed shock absorber model in a quarter car suspension system.

The complete shock absorber model is obtained by combining two different techniques. The model thus obtained is validated with the results obtained from the experiment. Lastly, the combined (hybrid) model of the shock absorber is incorporated with 2 degrees of freedom quarter car suspension model to determine the response of the hybrid model. The random road profile is considered as input excitation to a quarter car model and performance characteristics of the vehicle such as body acceleration, body displacement, and suspension deflection is analyzed for linear, piecewise linear and combined (hybrid) shock absorber model using Simulink.

The novelty of the present study is to develop a hybrid shock absorber model to capture hysteresis characteristics of the damper based on data obtained from an experiment carried out in the laboratory. The model thus developed is subsequently utilized to predict the response behavior of the vehicle under different road excitation.

2. Experimental set-up for car shock absorber dynamic analysis

In order to determine the dynamic properties of a shock absorber, an experiment is carried out on an INSTRON 8801 servo-hydraulic machine. The shock absorber is commercially used in Ford car running on Indian roads. The experimental set-up, a complete testing solution, is shown in Fig. 1. The shock absorber is fixed between the dynamic load cell and fixture (see Fig. 1(a)). The fixture (Fig. 1(b)) is fabricated as per the dimensions of the damper. The INSTRON 8801 is supplied with data acquisition system (Fig. 1(c)) that provides complete control over input and output data.

Force-displacement properties of the shock absorber are obtained with sinusoidal excitation having different amplitudes and frequencies. The values of input data (Table 1) applied for excitation purpose are chosen based on the experiments being conducted in open literature and specification given in Gillespie [45] and Wong [46].

2.1. Force-displacement and force-velocity characteristics curve

The Figs. 2 and 3 illustrate the nature of force-displacement and force-velocity characteristics of the damper by varying

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