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Non-linear analysis of a quarter-car model with stroke-dependent twin-tube shock absorber

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ABSTRACT

The work presents results of the analysis of a quarter-car model with a modified twin-tube hydraulic shock absorber. In comparison with a classical damper, this shock absorber possesses an additional double-chamber cylinder. The flow of oil into these chambers is controlled by relative displacement of the auxiliary piston and by pressure difference in the adjacent chambers. The introduced nonlinear spring element – bumper – protects the shock absorber against damage in the case of large amplitudes of excitations. Performance efficiency of the shock absorber model within the range of both large amplitudes and high excitation frequencies ensures that the change of the oil bulk modulus resulting from a change in pressure is accounted for. The introduction of additional chambers into the shock absorber leads to a change in the characteristics of the damping force. Within the range of small amplitudes and high frequencies the system acts like a shock absorber with a soft characteristic, which improves the driving comfort. In resonance ranges the increase in the damping force ensures higher driving safety. The analysis of the system response to the harmonic excitation of variable frequency and amplitude as well as to the random excitation permits to examine the impact of excitation parameters and construction parameters on the indicators characterizing the driving comfort and safety. The results of numerical simulations are illustrated with the graphs of time histories, spectral analyses, characteristics of the damping force, and others, illustrating the processes of controlling oil flow.

1. Introduction

Ensuring good comfort and a high level of safety while driving a car vehicle is possible due to various types of suspensions. The most common ones are passive suspensions, in which spring and damping elements of nonlinear characteristics are used. Better driving control is ensured by the so-called 'hard suspensions' generating a higher damping force. Such suspensions, however, reduce the automobile passengers' travel comfort. A well designed shock absorber should minimize vibrations of the car bodywork and ensure the appropriate road surface grip of the wheels. In order to accommodate these contradictory requirements, in some suspensions hydraulic shock absorbers are applied with an additional bypass, controlled by relative displacement of the piston [1,2]. In the case of large amplitudes of excitations the characteristics of such

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a damper is close to the hard characteristics. In other cases, the damping force is smaller (soft characteristics), thus ensuring the appropriate driving comfort.

In order to verify the effectiveness of the damper performance, most frequently quarter-car models [2–8] or – much more seldom – half-car models [9–12] are analyzed. The analysis of a quarter-car model indicates the presence of two basic resonance ranges. In the first range of lower frequencies in the form of vibrations, the vibrations of the so-called sprung mass – i.e. car bodywork – are dominant, therefore the indicators responsible for the driving comfort are important within this range. For comfort assessment root-mean-square (RMS) values or maximum values of displacement, velocity and acceleration of the sprung mass are often made use of [12,13]. In the second range of higher frequencies vibrations of the so-called un-sprung mass, that is mainly wheels, are observed. In extreme cases there may appear momentary separation of the wheels from the road surface, which significantly influences driving safety. The level of safety is measured by indicators dependent on the minimal reaction (e.g. the EUSAMA indicator [8]) or on the reaction dynamic component [13]. The decrease in the reaction is accompanied by worse wheel grip and control ability as well as lowered effectiveness of transmitting driving and braking forces. The performance quality criterion regarding the analyzed vibro-isolation system should ensure a compromise between the level of passengers' comfort and their safety while travelling.

The main cause of vibrations which exert an influence on the automobile driver is kinematic excitation resulting from an uneven road surface. In numerical simulations the road profile is frequently described by a random function [4,10,14,15] or a harmonic function with a constant or variable amplitude. For example, Funke [16] determines the characteristics of damping force of a mono-tube shock absorber by analyzing the responses of the system to a harmonic excitation of a limited value of the maximum velocity. Within the range of high frequencies smaller amplitudes of excitations are accepted respectively. Also Titurus [17] deals with the problem of identification on the basis of the system responses to the excitation with a constant velocity in a given section. Impulse functions [18,19], e.g. a unit step function, are applied when a car vehicle overcomes obstacles (e.g. road bumps).

The analysis of an automobile model requires an introduction of such a model of a shock absorber which will well describe its basic features, at the same time allowing to analyze the impact of its important parameters on the introduced quality indicators. Works which deal with the problem of modelling twin-tube [2,16,20–24] and mono-tube [3,17,25,26] shock absorbers are different mainly in their approach towards the description of the oil flow through valves. In numerous shock absorbers design solutions some of the flow canals are covered with a stack of resilient plates, deflecting gradually under the influence of the resultant pressure force. The flow through these canals is controlled by the difference in oil pressures in the adjacent shock absorber chambers. Most of the works assume a model of a rigid plate pressed by a linear or nonlinear spring. Such a model is proposed among others by: Alonso [20], Farjoud and Ahmadian [25], Talbott [26]. Benazis [27], while analyzing the impact of valve vibrations on the acoustic comfort, additionally accounts for the inertial and visco-elastic properties of the plates. In bypass shock absorbers the oil flow is additionally controlled by relative displacement of the piston. For example, Lee and Moon [2] propose a twin-tube displacement-sensitive shock absorber, in which the oil flow depending on piston displacement is realized through an adequate shape of the surface of the inner cylinder.

In some works [20] the problem of cavitation is analyzed that results from rapid changes in oil pressure. The phenomenon of cavitation can be taken into account by the introduction of the so-called effective bulk modulus. The works [28,29] present various descriptions of the dependency of the effective bulk modulus on the oil pressure and on the percent air content in oil.

This work proposes a new design of the twin-tube hydraulic shock absorber, which consists in the introduction of an additional cylinder which is rigidly connected with the piston rod. A movable mass which controls the oil flow is placed in the cylinder. Similar construction solutions for shock absorbers are described in the works [30,31].

The result of the proposed modification of the shock absorber is the dependence of the damping force characteristic on the amplitude and frequency of excitation. For well-chosen construction parameters of the shock absorber, its characteristics within the range of small amplitudes of excitation (and mostly high frequencies) is definitely much softer than in the case of larger amplitudes.

The characteristic of a classical damper is a non-linear characteristic which, however, to a small extent depends on relative displacements of the piston. Therefore, the parameters of the classical damper are selected depending on its application, differently in the case of off-road vehicles (for worse road surfaces) than for passenger cars, i.e. for better road surfaces. The new shock absorber design proposed in the work allows to better reconcile the requirements referring to comfort and safety of driving.

The purpose of the work is to design a shock absorber with variable characteristics ensuring better driving comfort on a good road, with unchanged properties in the case of worse road surfaces in comparison to the classical damper with a "hard" characteristic.

The numerical analysis of a quarter-car model with the shock absorber proposed in this paper shows that for small amplitudes and high frequencies the system behaves like a shock absorber with a soft characteristic, which improves the driving comfort. Within the resonance ranges, however, an increase in the damping force ensures greater driving safety. The results of numerical simulations presented in the paper illustrate the impact of various types of excitation and essential parameters of the shock absorber on the introduced indicators of damping efficiency.