Improving ride comfort by optimizing the parameters of a quarter car model with a power law damper

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Abstract. Suspension systems play a very important role in the vehicle performance as they are directly linked to improve and enhance the comfort of passengers. The working of a suspension arrangement depends strongly on the selection of suspension parameters like the spring stiffness and the damping coefficient. In this present study the parameters of a passive suspension with a power law damper are optimized for motion over a bump using genetic algorithm technique keeping passenger comfort in mind. It is seen that the best combination of suspension parameters results in selection of higher damping, lower spring stiffness and a lower value of power law index. It is also seen that the increase in the values of damping power index will result in the reduction of the suspension performance.

Keywords: Quarter car model, Suspensions, Optimization, Genetic algorithm.

1. Introduction

Suspensions in the automobiles are of greater importance considering the passenger comfort and safety. A good suspension will eliminate all type of disturbances arising from the road irregularities or the bumps and provide a comfortable and smooth ride to the passenger and the rider.

Suspensions can be active or passive depending on the amount of money spent in buying an automobile. Generally active suspensions are costlier due to their complexities and other factors. Passive suspensions are the widely used suspensions in most of the automobiles due to their lower costs, high reliability and simplicity, therefore a study has been conducted for the passive suspensions and also this study will present a model having the improved and optimized parameters which will enhance the ride comfort to the passengers.

Lozia et al. [1] considered a passive suspension system of 2 DOF and optimized the damper characteristics by driving it on three roads of different quality and performing simulation at four different vehicle speeds. They had also considered the effect of sliding friction in the nonlinear model and had shown that the variation between linear and nonlinear model increases because of this factor and also it is the prime factor of variation especially when the vehicle is driven on rough roads. Mitra et al. [2] improved the parameters of passive suspensions and alleviated the passenger’s ride comfort. They had compared the results before and after optimizing the parameters by using GA technique and
found out that the decay in the amplitude of driver head acceleration correspondingly increases the ride comfort. Jamali et al. [3] calculated the motion of passive suspension system using 2 DOF quarter car model and analyzed the frequency feedbacks of the system with different values of damping constant. Their study can be used to design a more realistic vehicle suspension system by considering the effect of road disturbances. Puneet et al. [4] optimized the control parameters for the passive suspension systems for improving the passenger ride comfort and vehicle road contact. They further used genetic algorithm technique and determined the appropriate values of the damping coefficients and spring constants which resulted in improved road holding and ride comfort to the passengers.

Mahajan et al. [5] in their study determined the behavior of the suspension system for sine input with variable frequencies and had shown that the increase in the frequency of the sine wave will result in the decrease in the settling time of sprung mass acceleration which will directly result in the effect the passenger ride discomfort. Further, Gadhavi et al. [6] in their study utilizes three different algorithm techniques in passive suspensions by moving over a road profile having two sinusoidal depressions. Comparisons were made in between all three techniques and a better one is introduced for improved ride comfort. Fossati et al. [7] in their study optimized the full car model of passive suspensions on a random road profile. By using the NSGA-II technique they minimized the three objectives hence thereby increasing the ride comfort of the rider and passengers. Their optimization parameters can be used in the effective design of passive suspensions providing improved ride comfort for the passengers. Several other researches [11] - [14] on the passive suspensions have been carried out for improving the ride comfort by optimizing the suspension parameters. From above it is very much clear that a number of researches have been conducted on the passive suspensions and the optimum selection of the suspension parameters is one of the most significant factors to be considered in the design of passive suspensions.

Dobriyal et al. [15] had considered dynamics of passive suspensions with nonlinear power law damper and conducted its dynamic analysis using quarter car model. This paper focuses on extending this previous work by optimizing the suspension parameters using the genetic algorithm on the quarter car model and the effect of varying the damping power index on the oscillations has been considered which had not been done previously. The paper will contribute to the designing of passive suspensions with the optimized parameters having the values which will provide better ride comfort to the passengers. This information can be further used to improve the performance and quality of passive suspensions.

2. Methodology

2.1. Modeling

The fig. 1 below shows the schematic of quarter car suspension considered for analyzing the behavior of the passive suspension. The mass of the body and the various other components supported on the suspensions is the sprung mass considered as $m_s$, and the mass of the wheels, suspensions and its parts etc. are the unsprung masses considered as $m_u$. The sprung mass is dangling on the suspension spring designated as $k_s$. The damper is indicated in the figure as $c_s$ representing damping coefficient of suspension. This unsprung mass is held on the tire having spring stiffness and damping coefficient as $k_u$ and $c_u$, respectively. $Z_r$ is the vertical height from the road surface; $Z_s$ and $Z_u$ in the fig. 1 are the displacements of sprung mass and unsprung mass.
The quarter car model comprising of equations of motion, can be derived using Newton’s second law of motion, the second order differential equations are given by:

\[
\ddot{z}_s = -\frac{k_s}{m_s} (z_s - z_u) - \frac{c_s}{m_s} Sgn(\dot{z}_s - \dot{z}_u) \left| \dot{z}_s - \dot{z}_u \right|^n - g \\
\ddot{z}_u = \frac{k_u}{m_u} (z_u - z_s) + \frac{c_s}{m_u} Sgn(\dot{z}_u - \dot{z}_s) \left| \dot{z}_u - \dot{z}_s \right|^n - \frac{k_u}{m_u} (z_u - z_s) - \frac{c_u}{m_u} (\dot{z}_u - \dot{z}_s) - g
\]

where first and second derivatives \(z_s, z_u\), and \(z_r\) represent their velocities and accelerations, respectively, \(Sgn\) is the signum function and \(n\) represents the power law index for the damper. Table 1 shows the numerical values of different parameters.

| Parameter | Value       |
|-----------|-------------|
| \(m_s\)  | 500 kg      |
| \(m_u\)  | 30 kg       |
| \(k_s\)  | 20000 N/m   |
| \(c_s\)  | 1500 N-s/m  |
| \(k_u\)  | 200000 N/m  |
| \(c_u\)  | 0 N-s/m     |
| \(n\)    | 1           |

2.2. Optimization
Genetic algorithms are generally used to achieve high-quality solutions to optimize and explore problems by confiding on biologically motivated operators such as mutation, crossover and selection. GA technique [8] is widely used in the researches of engineering applications as they provide the robust solutions.
In spite of the availability of numerous optimizing techniques GA has been used in this study because of its easier implementation and better producing results [9]. Applications of GA in engineering field start from first generations [10]. The algorithm then brings forth an array of new and unique populations. At each step, the algorithm utilizes the individuals in the current generation to devise the later population.

Minimizing the sprung mass acceleration will result in the improvement of ride comfort therefore the optimization problem can be defined as follows:

$$\min_{k_s, c_s, n} \ddot{x}_s = f(z_s, z_u, \dot{z}, \dot{z}_u, k_s, c_s, n)$$

subjected to:

$$k_{s_{\text{min}}} \leq k_s \leq k_{s_{\text{max}}}$$

$$c_{s_{\text{min}}} \leq c_s \leq c_{s_{\text{max}}}$$

$$n_{\text{min}} \leq n \leq n_{\text{max}}$$

The fitness function for GA is based on the integral time absolute error (ITAE), in ITAE the absolute value of the sprung mass acceleration is multiplied by time and then integrated over time.

3. Simulation Results

Simulation studies are conducted to analyze the behavior of the suspension system over a bump. The road profile with a bump is shown in Fig. 2(a), where a bump of 10 cm height appears at 5 s. In Fig. 2(b-c), absolute acceleration and acceleration of the sprung mass are plotted with respect to time over the bumpy road, which are main measure of ride comfort, since less oscillations lead to more ride comfort. From these results, it can be concluded that compared to the reference value of the damping power index ($n=1$), lower value of $n$ results in less oscillations ($n=0.8$), while higher value shows more oscillations ($n=1.2$). Moreover, lower value of $n$ leads to less spring compression as shown in Fig. 2(d). Thus, it is interesting to find the optimized value of $n$ along with the optimized values of $k_s$ and $c_s$ in order to minimize the sprung mass acceleration as defined in equation (3).
Fig. 2: (a) Road profile with respect to time, (b) absolute sprung mass acceleration, (c) acceleration of sprung mass, and (d) spring compression on the given road profile having various values of the damper’s power index $n$.

Fig. 3: Simulation results before and after the optimization while traveling on the given road profile with a bump (a) absolute acceleration of sprung mass, (b) sprung mass acceleration, (c) spring compression, and (d) sprung mass displacement.
In Fig. 3, simulation results are shown for the working of the suspension system with and without the optimization. The blue curves represent the results without optimization, where $k_s=20000$ N/m, $c_s=1500$ N-s/m, and $n=1$; while, the red curves represent the results after optimization, where $k_s=15000$ N/m, $c_s=1933$ N-s/m, and $n=0.72$. Refer to Fig. 3 (a)-(b), it can be observed that after using the optimized values, the oscillations of absolute sprung mass acceleration and sprung mass acceleration settle down rapidly which ensures better ride comfort. In addition, from Fig. 3 (c)-(d), it can be also be observed that less oscillations in spring compression and sprung mass displacement occur after optimization.

4. Conclusion

The primary reason of suspension systems being installed in a vehicle is to provide a smooth and comfortable ride to the passengers. For a passive suspension system selecting optimum suspension parameters is a delicate balance between various competing factors and always a challenge. In the present work we have optimized the parameters of a model of a quarter car with a power law damper for motion over a bump for maximum ride comfort. Sprung mass acceleration is taken to be an indicator for the ride comfort with lower acceleration corresponding to higher ride comfort. Following conclusions have been drawn from the results discussed in the previous section:

1. Optimization is performed using genetic algorithm GA. The optimization results in a lower value of spring stiffness which is usually associated with better ride comfort.
2. A higher value of damping is also indicated which is likely due to the fact that a higher damping value will damp out the oscillations faster.
3. Selection of a lower value of $n$ could be due to the fact that it results lesser spring compression (as seen in the simulation results) and hence less force on the sprung mass.

In the future work instead of bump, road irregularities can be considered for passenger ride comfort in optimizing the suspension parameters using a power law damper.

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