Influences of the Suspension Parameters on the Vehicle Suspension Performance for a Terrain Vehicle

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Abstract: This paper describes an effective methodology for evaluation of the suspension parameters intended to be used for a terrain vehicle. The objective of this approach is to make quick analyses of the sensitivity of the vehicle suspension parameters. For the purpose of developing such a methodology, a mathematical modeling of a quarter vehicles suspension system is developed. Sensitive analysis of the suspension parameters is performed by employing the standard deviation of the vehicle body acceleration, dynamic tire load, and suspension travel. Sensitivity analysis results have shown that the spring stiffness, damping coefficient, tire stiffness and sprung mass have substantial influence on the ride comfort and road holding, while un-sprung mass on the other side has much lower impact in performance of the vehicle suspension system.

Key words: Terrain vehicle, suspension parameters, ride comfort, road holding, suspension travel.

1. Introduction

To improve ride comfort and road holding, designers have always shown great interest in designing new and better suspension systems. It is well known that the key issues to be achieved when designing a vehicle suspension system are to maintain at all times qualitative contact between tires and road surfaces irrespective of the quality of the road surfaces and to ensure best possible isolation of the vehicle body from vibration caused by road disturbances [1-2]. The ride comfort is related to the vehicle’s body acceleration; road holding is dependent from the contact between tire and road surface computed by dynamic tire load, while suspension travel presents the relative motion between vehicle body and wheel assembly. In general, vehicle suspension systems may be categorized as passive, semi-active and active systems [3-4]. The passive suspension systems are used mostly in passenger vehicles. This system includes parallel mounting of the conventional spring and shock absorber. Spring and shock absorber assembly are assumed to have linear characteristics. Although this suspension system do not fulfill all expectations about comfort and safety are used widely.

The aim of this paper is to develop an effective methodology for analyzing of the sensitivity of the suspension parameters. Sensitivity analysis attempts to reach an optimal solution between three conflicting criteria’s: vehicle body acceleration, dynamic tire load and suspension travel.

The paper is organized as follows: Section 2 describes mathematic modeling of the vehicle suspension system; section 3 introduces standard deviation of the ride comfort, road holding and suspension travel; section 4 discusses the sensitivity analysis of the suspension parameters; section 5 gives results and discussion; section 6 contains conclusions.

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2. Mathematic Modeling

The Quarter Vehicle Model (QVM) for a long time has been the par excellence tool used for evaluation of the vehicle suspension design [5]. It is a simple model and in relation to ride comfort and road holding gives qualitative data. The QVM consist from two masses. One is sprung mass \( M_s \), while other is un-sprung mass \( M_u \) (Fig. 1). The sprung mass represents approximately \( \frac{1}{4} \) vehicle body mass, while un-sprung mass represents one wheel mass of the vehicle. For the purpose of simplifying the model, spring stiffness coefficient \( k_s \), tire stiffness coefficient \( k_t \), and damping coefficient \( c_d \) are assumed to have linear characteristics.

The equation of the motion for a QVM can be determined by applying Newton’s equation, written by the following expressions:

\[
M_s \cdot \ddot{y}_s = -k_s \cdot (y_s - y_u) - c_d \cdot (\dot{y}_s - \dot{y}_u)
\]

\[
M_u \cdot \ddot{y}_u = k_s \cdot (y_s - y_u) + c_d \cdot (\dot{y}_s - \dot{y}_u) - k_t \cdot (y_r - y_u)
\]

where \( \ddot{y}_s, \dot{y}_s, y_s \) and \( \ddot{y}_u, \dot{y}_u, y_u \) denote acceleration, velocity and displacement of the sprung and un-sprung masses. Eq. (1) presents system of the second order non-homogeneous linear differential equation.

3. Standard Deviation of the Ride Comfort, Road Holding and Suspension Travel

The ride comfort is evaluated by computing the standard deviation of the vertical body acceleration \( \sigma_a \). Higher values result in greater vehicle discomfort. To obtain optimal passenger comfort in regards to the vehicle suspension system, the standard deviation of the vertical body acceleration should be as low as possible. The standard deviation of the vehicle body acceleration \( \sigma_a \), is written as follow [6]:

\[
\sigma_a = \left[ \frac{A_h \cdot v}{2 \cdot c_d} \left( \frac{M_u}{c_d^2 M_s^2} \cdot k_s^2 + \frac{M_s}{c_d^2 M_u^2} \cdot k_t^2 + \frac{c_d}{M_s M_u^2} \cdot k_t \right) \right]^{0.5}
\]

The road holding is related to the standard deviation of the dynamic tire load acting between ground surface and tire \( \sigma_F_{z} \). If the dynamic tire load oscillates too much, then the contact between the tire and ground surface is weak. Consequential the vehicle maneuverability and steering is in question. The standard deviation of the dynamic tire load \( \sigma_F_{z} \), is given by the following expression [6]:

\[
\sigma_F_z = \frac{A_h \cdot v}{2 \cdot c_d} \left( \frac{(M_s + M_u)^3}{M_s^2 M_u^2} \cdot k_t^2 + \frac{(M_s + M_u)^2}{M_s^2} \cdot c_d \cdot M_u \cdot k_t \right)^{0.5}
\]

The suspension travel is evaluated by the standard deviation of the relative motion between sprung and un-sprung masses \( \sigma_t \), which is determined by the following expression [6]:

\[
\sigma_t = \left\{ \frac{A_h \cdot v}{2 \cdot c_d} \right\}^{0.5}
\]

The standard deviations of both dynamic tire load and suspension travel are closely related to the active vehicle safety [6].

The suspension parameters given for a terrain vehicle are taken from Ref. [7] such as: \( k_s = 55227 \) N/m, \( c_d = 5230 \) Ns/m, \( k_t = 201441 \) N/m, \( M_s = 295 \) kg and \( M_u = 39 \) kg, \( A_h = 1.4 \times 10^{-5} \) m [6].

Fig. 2 illustrates influences on the suspension parameters shows above, resulting from the standard deviation of the ride comfort, road holding and suspension travel, in function of vehicle speed and road roughness, substituted into Eqs. (2)-(4).

From Fig. 2, it can be observed that the values of the ride comfort, road holding and suspension travel significantly decrease when vehicle speed goes up. From this fact, it is concluding that to improve vehicle performance, it is necessary to perform a detail sensitivity analysis of the suspension parameters.
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4. Sensitivity Analyses of the Terrain Vehicle Suspension Parameters

Investigation of the vehicle dynamic behavior through the QVM is performed by employing Eqs. (2)-(4). These expressions are used for sensitive analyses of the suspension parameters, as given in Table 1.

To evaluate the terrain vehicle suspension sensitivity based on ride comfort, road holding and suspension travel, it is necessary to employ the Eqs. (5)-(7) for range of the suspension parameters values presented in Table 1, which is written in the following expressions:

\[
\frac{\sigma_{ar}(b_i, \text{reference})}{\sigma_{ar}(\text{reference})}; \text{ for } i = 1...5 \quad (5)
\]

\[
\frac{\sigma_{Fz}(b_i, \text{reference})}{\sigma_{Fz}(\text{reference})}; \text{ for } i = 1...5 \quad (6)
\]

\[
\frac{\sigma_{s}(b_i, \text{reference})}{\sigma_{s}(\text{reference})}; \text{ for } i = 1...5 \quad (7)
\]

where \( b_i = b_1, b_2, \ldots, b_5 \) determine range of the suspension parameters \( (b_f = k_{sr}, b_2 = c_{dr}, b_3 = k_t, b_4 = M_{sr}, \text{ and } b_5 = M_u) \) while term \( \text{reference} \) indicates reference suspension parameters such as \( k_s, c_d, k_t, M_s, \text{ and } M_u \) tabulated in Table 1.

In this manner, the original five dimensional problems are reduced into one dimensional problem, illustrated graphically by curves shown in Figs. 3-5. Each curve has been obtained from the vehicle data shown in Table 1, and by varying one single parameter (i.e., \( k_{sr}, c_{dr}, \text{ etc.} \) ) while the other single parameter keeping constant (i.e., \( k_s, c_d, \text{ etc.} \) ).

The following presented graphs reflect the non-dimensional form of the standard deviation of interest \( \sigma_{j}(b_j, \text{reference}) \) divided by corresponding reference values of \( \sigma_{j}(\text{reference}) \).

5. Results and Discussion

In this section, influence of each suspension parameters on the vehicle performance is presented. Results are obtained by employing equations for ride comfort, road holding and suspension travel and reference data taken from Table 1.

Fig. 3 shows influences of suspension parameters in ride comfort, i.e., \( \sigma_{ar}(b_i, \text{reference})/\sigma_{ar}(\text{reference}) \). As stated before, each curve has been obtained by varying one single parameter whereas, while keeping other single parameters constant and equal.
### Table 1  Reference data, lower and upper limits of the suspension parameters.

<table>
<thead>
<tr>
<th>Suspension parameters</th>
<th>Unit</th>
<th>Reference data</th>
<th>Lower and upper limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring stiffness. coefficient</td>
<td>N/m</td>
<td>$k_s$</td>
<td>$55227$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$k_{sr}$</td>
</tr>
<tr>
<td>Damping coefficient</td>
<td>Ns/m</td>
<td>$c_d$</td>
<td>$5230$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$c_{dr}$</td>
</tr>
<tr>
<td>Tire stiffness</td>
<td>N/m</td>
<td>$k_t$</td>
<td>$201441$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$k_{tr}$</td>
</tr>
<tr>
<td>Sprung mass</td>
<td>kg</td>
<td>$M_s$</td>
<td>$295$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$M_{sr}$</td>
</tr>
<tr>
<td>Un-sprung mass</td>
<td>kg</td>
<td>$M_u$</td>
<td>$39$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$M_{ur}$</td>
</tr>
</tbody>
</table>

![Fig. 3  Sensitivity analysis of the ride comfort as function of the suspension parameters.](image)

Fig. 3  Sensitivity analysis of the ride comfort as function of the suspension parameters.

![Fig. 4  Sensitivity analysis of the road holding as function of the suspension parameters.](image)

Fig. 4  Sensitivity analysis of the road holding as function of the suspension parameters.

From Fig. 3, it can be concluded that

- The value of the ride comfort is influenced by the damping coefficient;
- The value of the ride comfort is significantly influenced by the value of spring stiffness coefficient;
- The value of the ride comfort is depended on the tire stiffness;

![Fig. 5  Sensitivity analysis of the suspension travel as function of suspension parameters.](image)

Fig. 5  Sensitivity analysis of the suspension travel as function of suspension parameters.

- The value of the ride comfort correlates strongly with sprung mass;
- The value of the ride comfort does not have influence on the un-sprung mass.

Taking into consideration that higher value of the damper and spring stiffness coefficient result in considerable reduction of the comfort, to reduce those values to an optimum value should be always aimed.

It should have to be kept in mind that though that soft spring results in large variations of the equilibrium position and vehicle becomes unstable.

![Fig. 4](image)

Fig. 4 presents sensitivity analysis of the road holding, i.e., $\sigma_{Fz}(h_r, \text{reference})/\sigma_{Fz}(\text{reference})$ as a function of the suspension parameters. Each curve has been obtained by varying single parameters while others ones being constant and equal.

By inspection of Fig. 4, it is observed that

- The road holding is influenced by the damping coefficient;
- The road holding increases significantly to the value of spring stiffness coefficient;
• The road holding is linearly depended by the value of tire stiffness;
• The road holding have low influence on the sprung mass;
• The road holding is significantly influenced by the un-sprung mass.

Fig. 5 gives a sensitivity analysis of the suspension travel, i.e., $\sigma_s(b, \text{reference})/\sigma_s(\text{reference})$ as a function of the suspension parameters. As similarly shown in Figs. 3-4, each curve has been obtained by varying single parameters, the others ones being constant and equal.

It is also observed from Fig. 5 that

• Suspension travel is independent from the spring stiffness coefficient;
• Suspension travel is strongly influenced by the damping coefficient;
• Suspension travel is not affected by the tire stiffness;
• Suspension travel is highly influenced by the sprung mass;
• Suspension travel significantly is impacted by the effect of the un-sprung mass.

Considerations given above are evaluated by Eqs. (2)-(7) and do not depend from vehicle speed. Finally, based on evaluation of sensitivity of the suspension parameters, it is concluded that the reference values of the suspension parameters are close to optimum values. This means that passive suspension system gives sufficient ride comfort, ride holding and suspension travel.

6. Conclusions

An effective methodology for sensitivity analysis of the suspension parameters for a terrain vehicle has been investigated. To develop such methodology, the mathematical modeling of the quarter vehicles model is taken in consideration. The sensitive analysis of the suspension parameters is performed by evaluation of ride comfort, road holding as well as suspension travel. Obtained results have found that the ride comfort is not depended on un-sprung mass; road holding is not related to the sprung mass, while suspension travel is highly influenced by damping coefficient and sprung mass, respectively.

The higher values of the spring stiffness coefficient and damper coefficient result in considerable reduction of the comfort, while soft spring gives considerable comfort but produces large variations from the equilibrium position and vehicle becomes unstable.

In summary, the reference suspension parameters are close to an optimum.

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References