Design of Optimal Linear Suspension for Quarter Car with Human Model using Genetic Algorithms

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ABSTRACT
This paper presents an optimization of a four-degrees-of-freedom vehicle’s human with seat suspension system using genetic algorithms (GA) to determine vehicle suspension parameters to achieve the best comfort of the human. Maximum allowed vertical acceleration of the human body and the suspension working space were used as constrained limits in this study. The genetic algorithm is applied to solve the optimization problem. The optimization results are compared through step and sinusoidal excitation of the seat suspension system for the optimal and currently used suspension systems. In case of sinusoidal profile excitation, results showed that RMS acceleration of the driver, seat suspension working space and sprung mass are reduced by about 21%, 21.5% and 20.3%, respectively. At step profile excitation, RMS acceleration of the driver, seat suspension working space and sprung mass are reduced by about 24%, 24.98% and 7.15%, respectively. The optimal design parameters of the suspension systems obtained are $k_a=10039$ N/m and $c_s=900$ N.s/m in case of sinusoidal input and $k_a=10030$ N/m and $c_s=913$ N.s/m in case of step input, respectively.

Categories and Subject Descriptors
Genetic Algorithms

General Terms

Keywords
Biodynamic response, Ride-comfort, Simulation, Genetic algorithms.

1. INTRODUCTION
Today, a rebellious race is taking place among the automotive industry so as to produce highly developed models. One of the performance requirements is advanced suspension systems which prevent the road disturbances to affect the passenger comfort while increasing riding capabilities and performing a smooth drive. While the purpose of the suspension system is to provide a smooth ride in the car and to help maintain control of the vehicle over rough terrain or in case of sudden stops, increasing ride comfort results in larger suspension stroke and smaller damping in the wheel hop mode [1].

The vibrations cause the operator’s whole body to vibrate, as opposed to just one part of their body, says their hand or foot. Harmful effects of whole-body vibration are experienced when the exposure time is longer than the recommended standard set by ISO 2631-1 [2]. The reported data on biodynamic responses of the seated and standing human body exposed to whole-body vibration along different directions and the associated experimental conditions are systematically reviewed by Rakheja et al. [3], in an attempt to identify datasets that are likely to represent comparable and practical postural and exposure conditions. The vibration isolation efficiency of seating has been evaluated by Paddan and Griffin [4], in 100 work vehicles in 14 categories. They concluded that the severity of whole-body vibration exposures in many work environments can be lessened by improvements to seating dynamics. Stein et al., [5] described a simplified simulation of two configurations of the fore-and-aft seat suspension system based on the laboratory measurements of the seat vibration isolation performance. The optimization study shows the attainable vibration mitigation limits for a horizontal suspension system. A 7-DOF vehicle’s driver model with seat suspension system was presented by Abbas el al. [6]. A genetic algorithm is applied to search for the optimal parameters of the seat in order to minimize seat suspension deflection and driver’s body acceleration to achieve the best comfort of the driver. The simulation results were compared with the ones of the passive suspensions through step and sinusoidal excitation of the seat suspension system for the currently used suspension systems.

On the other hand, vehicle suspension systems aim to improve the vehicle performance which involves; Ride comfort, handling, road holding, suspension deflection, and static deflection. Sun [7] presented an optimum concept to design “road-friendly” vehicles with the recognition of pavement loads as a primary objective function of vehicle suspension design. The results showed that

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tires with high air pressure and suspension systems with small damping will lead to large tire loads. The parameter sensitivity analysis of a passenger/seat model that can be used for ride comfort assessments was discussed by Brogioli et al. [8]. The most important conclusion of their research is that the parameters referring to posture have proved to influence ride comfort to a great extent. Other relevant but less important parameters are: the stiffness and damping of the seat, the geometry of the seat, the size and inertia properties of the body segments, and the stiffness and damping of the different parts of the human body. A generalized nonlinear model is formulated by Bouazara et al. [9], for the dynamic analysis of suspension seats with passive, semi-active and active dampers. It is concluded that the comfort performance of a suspension seat with semi-active and active dampers can be considerably enhanced by 20–30%. The spring and damper settings that will ensure optimal ride comfort of an off-road vehicle, on different road profiles and at different speeds has been investigated by Uys et al. [10]. It is found that optimizing for a combined driver plus rear passenger seat weighted root mean square vertical acceleration rather than using driver or passenger values only, returns the best results.

For efficiency, genetic algorithm is employed to search for the parameters like damping ratio and spring constant to achieve an optimum trade off among ride comfort, handling quality, and suspension stroke simultaneously for random input. A dynamic model of an on-highway truck seat is proposed by Hassannin et al. [11], to improve a highway truck seat. Genetic algorithms are used to obtain the coefficients of a seat suspension system controller parameters. The results showed that an active suspension using genetic algorithms has successfully managed to improve all the dynamic performance parameters of the truck seat with minimum actuator force. GA optimization is used by Baumal et al. [12] to determine both the active control and passive mechanical parameters of a vehicle suspension system, to minimize the extreme acceleration of the passenger’s seat, subjected to constraints representing the required road-holding ability and suspension working space. A complete study on lumped parameter models for seated human subjects without backrest support under vertical vibration excitation has been carried out by Liang and Chiang [13], based on analytical study and experimental validation. An optimization of a 4-DOF quarter car seat and suspension system was presented by Gündoğdu [14], using genetic algorithms to achieve the best performance of the driver. The optimization results were compared through step and frequency responses of the seat and suspension system for the optimum and currently used suspension systems. Comparatively better results were obtained from the optimized system in terms of resonance peaks and vibration dose value.

The design of a passive vehicle suspension system was handled by Sun et al. [15] in the framework of nonlinear optimization using a quarter-car model. The performance was measured by the aid of a GA which is applied to solve the nonlinear optimization problem to achieve the optimum design parameters of the suspension systems. A genetic algorithm method is applied to the optimization problem of a linear 1-DOF vibration isolator mount and the method is extended to the optimization of a linear quarter car suspension model [16]. Although the systems are linear, it is difficult to find such optimal relation analytically. The GA method increases the probability of finding the global optimum solution and avoids convergence to a local minimum which is a drawback of gradient-based methods.

The GA is used to solve the problem and results were compared to those obtained by simulated annealing technique and found to yields similar performance measures. A control scheme for the active suspension in a 4-DOFs half-car model is presented by Hada et al. [17]. A force cancellation control scheme is used to isolate the sprung and the unsprung masses. Road following springs are applied for the sprung mass to follow the trend of the road surface condition and to maintain the suspension stroke within a reasonable range.

On the other hand, whole-body vibration is harmful to humans because it excites the natural frequency of the body. Whole-body vibration has many ill effects on the operators. Health effects can range from fatigue to permanent damage to the spine of the operator. Many studies have been conducted to link the exposure of whole-body vibration to common health problems experienced by operators of vibrating machinery. These studies show the effects of whole-body vibration, and some debate whether the ISO standard is strict enough [18-20]. Table 1 shows a number of vital body parts, and the corresponding natural frequencies.

### Table 1. Natural frequencies of the human body

<table>
<thead>
<tr>
<th>Body Part</th>
<th>Natural Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk</td>
<td>3-6</td>
</tr>
<tr>
<td>Eyeball</td>
<td>20-25</td>
</tr>
<tr>
<td>Chest</td>
<td>4-6</td>
</tr>
<tr>
<td>Thorax</td>
<td>3</td>
</tr>
<tr>
<td>Spine</td>
<td>3-5</td>
</tr>
<tr>
<td>Heart</td>
<td>4-5</td>
</tr>
<tr>
<td>Shoulders</td>
<td>2-6</td>
</tr>
<tr>
<td>Head</td>
<td>30</td>
</tr>
<tr>
<td>Stomach</td>
<td>4-7</td>
</tr>
<tr>
<td>Colon</td>
<td>20-25</td>
</tr>
</tbody>
</table>

2. **PROBLEM DESCRIPTION**

This paper is based on a 4-DOF human body developed by Abbas et al. [21] with linear seat suspension - coupled with quarter car model. In this model, a genetic algorithm is applied to search for the optimal parameters of the car suspension in order to minimize car suspension deflection and driver’s body acceleration to achieve the best comfort of the driver.

3. **MATHEMATICAL MODEL FORMULATION**

This paper is based on a 4-DOF human body developed by Abbas et al. [21] with linear seat suspension - coupled with quarter car model. In this model, a genetic algorithm is applied to search for the optimal parameters of the car suspension in order to minimize car suspension deflection and driver’s body acceleration to achieve the best comfort of the driver.

3.1 Proposed Model

This section is devoted to the mathematical modeling of the proposed model, including the biodynamic lumped human linear seat model coupled with quarter model of ground vehicles as illustrated in Fig. 1. It is assumed that the system does not vibrate in lateral or longitudinal directions, only subjects exposed to vertical vibration.

The human-body has a 4-DOF that proposed by Abbas et al. [21]. In this model, the seated human body was constructed with four separate mass segments interconnected by five sets of springs and dampers, with a total human mass of 60.67 kg. The four masses represent the following body segments: head and neck (m1), upper
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The arms and legs are combined with the upper torso and thigh, respectively. The stiffness and damping properties of thighs and pelvis are \((k_3)\) and \((c_3)\), the lower torso are \((k_2)\) and \((c_2)\), upper torso are \((k_1)\) and \((c_1)\), and head are \((k_0)\) and \((c_0)\). Typical design parameters for the model are listed in Table 2.

![Figure 1. Schematic diagram of biodynamic lumped human model coupled with quarter car model.](image)

Table 2. Model parameters

<table>
<thead>
<tr>
<th>Mass (kg)</th>
<th>Damping coefficient (Ns/m)</th>
<th>Spring constant (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_1=4.17)</td>
<td>(C_1=310)</td>
<td>(k_1=166990)</td>
</tr>
<tr>
<td>(m_2=15)</td>
<td>(C_2=200)</td>
<td>(k_2=10000)</td>
</tr>
<tr>
<td>(m_3=5.5)</td>
<td>(C_3=909.1)</td>
<td>(k_3=144000)</td>
</tr>
<tr>
<td>(m_4=36)</td>
<td>(C_4=330)</td>
<td>(k_4=20000)</td>
</tr>
<tr>
<td>-</td>
<td>(C_5=2475)</td>
<td>(k_5=49340)</td>
</tr>
<tr>
<td>(m_{uw}=35)</td>
<td>(C_{uw}=150)</td>
<td>(k_{uw}=15000)</td>
</tr>
<tr>
<td>(m_{wb}=250)</td>
<td>(C_{wb}=980)</td>
<td>(k_{wb}=16000)</td>
</tr>
<tr>
<td>(m_{tw}=35)</td>
<td>(C_{tw}=0)</td>
<td>(k_{tw}=16000)</td>
</tr>
</tbody>
</table>

The equations of motion of the model are:

\[
m_1\ddot{x}_1 = -c_1(\dot{x}_1 - \dot{x}_2) - k_1(x_1 - x_2),
\]

\[
m_2\ddot{x}_2 = c_1(\dot{x}_1 - \dot{x}_2) + k_1(x_1 - x_2) - c_2(\dot{x}_2 - \dot{x}_3) - k_2(x_2 - x_3) - c_3(\dot{x}_2 - \dot{x}_4) - k_3(x_2 - x_4),
\]

\[
m_3\ddot{x}_3 = c_2(\dot{x}_2 - \dot{x}_3) + k_2(x_2 - x_3) - c_4(\dot{x}_3 - \dot{x}_4) - k_4(x_3 - x_4),
\]

\[
m_4\ddot{x}_4 = c_3(\dot{x}_3 - \dot{x}_4) + k_3(x_3 - x_4) + c_5(\dot{x}_4 - \dot{x}_5) - k_5(x_4 - x_5),
\]

\[
m_{se}\ddot{x}_{se} = c_5(x_5 - x_{se}) + k_5(x_4 - x_{se}) - c_{se}(\dot{x}_{se} - \dot{x}_b) - k_{se}(x_{se} - x_{wb}),
\]

\[
m_{wb}\ddot{x}_b = c_{se}(\dot{x}_{se} - \dot{x}_b) + k_{se}(x_{se} - x_b) - c_4(\dot{x}_b - \dot{x}_w) - k_4(x_b - x_w),
\]

\[
m_{ww}\ddot{x}_w = c_4(\dot{x}_b - \dot{x}_w) + k_4(x_b - x_w) - c_5(\dot{x}_w - \dot{x}_o) - k_5(x_w - x_o).
\]

### 3.2 Input Profile Excitations

The excitation input from the road is transmitted to the vehicle floor. For the simplification of the dynamic modeling, it is assumed that there exists only the vertical motion of the vehicle. Both pitching and rolling motions are ignored in this study.

In this work, two types of the input profiles excitation are adopted to evaluate the proposed system. The sinusoidal profile is firstly used, which is described by:

\[
x_b = A \sin(\omega t)
\]

where, \(\omega = \frac{n v_c}{D}\), and \(A (0.035 \text{ m})\) is the hump height. \(D (0.8 \text{ m})\) is the width of the hump, and \(v_c\) is the vehicle velocity. This excitation assumed that the vehicle model travels with a constant velocity of 20 km/h (5.55 m/s). The second types of road is step profile. The step height was 0.035 m applied instantaneously.

### 4. OPTIMAL LINEAR SEAT SUSPENSION DESIGN

This paper is based on a 4-DOF human body developed by Abbas et al. [21] with linear seat suspension - coupled with quarter car model. In this model, a genetic algorithm is applied to search for the optimal parameters of the car suspension in order to minimize car suspension deflection and driver’s body acceleration to achieve the best comfort of the driver.

#### 4.1 Numerical Simulations

Displacement, velocity, and acceleration of the model in terms of time domain are obtained by solving equation. Equation 1, using MATLAB software ver. 7.12 (R2011a), dynamic system simulation software, Simulink. The initial conditions are assumed at equilibrium position. Fig. 2 shows the main simulink model of the suspension with human-body system.

#### 4.2 Optimization via Genetic Algorithms

In this section, optimization software based on stochastic techniques search methods, Genetic algorithm (GA) is a global search method based on the principle of natural section, which are related to the evolution in nature. "Survival of the fittest", Darwin’s principle of natural section, promoted the idea of
mimicking the natural section and using in the artificial life [22-24] possible solutions (individuals).

Genetic Algorithms (GAs), is employed to search for the optimal linear parameters of the car suspension to achieve the best comfort of the driver. The upper boundaries of car suspension parameters are selected based on previous studies. Table 3 shows the genetic algorithms parameters and its selected values.

<table>
<thead>
<tr>
<th>Table 3. Model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GA parameters</strong></td>
</tr>
<tr>
<td>Population size</td>
</tr>
<tr>
<td>No of generations</td>
</tr>
<tr>
<td>Fitness scaling</td>
</tr>
<tr>
<td>Crossover technique</td>
</tr>
<tr>
<td>Probability of crossover</td>
</tr>
<tr>
<td>Mutation technique</td>
</tr>
<tr>
<td>Generation gap</td>
</tr>
<tr>
<td>Lower boundary</td>
</tr>
<tr>
<td>Upper boundary</td>
</tr>
<tr>
<td>Objective function accuracy</td>
</tr>
</tbody>
</table>

Since the health of the driver is as important as the stability of the car, the desired objective is proposed as the minimization of a multi-objective function formed by the combination of not only car suspension working space \((\text{sw}_w=x_b-x_w)\) but also the head acceleration \((\ddot{x}_h)\), and seat mass acceleration \((\ddot{x}_{se})\). This study used the classical weighted sum approaches to solve a multi-objective optimization problem as equation:

\[
\text{OBJ} = w_1 (\ddot{x}_h) + w_2 (\text{sw}_w) + w_3 (\ddot{x}_{se})
\]

where, \(w_1\), \(w_2\) and \(w_3\) are weighting factors to emphasize the relative importance of the terms. Table 4 shows weighting factors used in excitation inputs.

<table>
<thead>
<tr>
<th>Table 4. Weighting factors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weight</strong></td>
</tr>
<tr>
<td>Excitation input</td>
</tr>
</tbody>
</table>

4.3 Optimization Procedure

First, the bounds of the design variables and initialize suspension design variables \(k_s\) and \(c_s\). Then \(k_s\) and \(c_s\) are passed into the proposed model to solve for the dynamic response (displacement, velocity, and accelerations values) of the system. The population is then coded into chromosomes, a binary representation of a solution (consisting of the components of the decision variables known as genes in the genetic algorithm). The whole population of chromosomes represents a generation. An evaluation function rates solutions in terms of their fitness. Here, fitness is a numerical value describing the probability for a solution (genome) to survive and reproduce. Only a portion of the population (survivors or solutions with higher fitness values) is selected for creating a new population (offspring production). This new population is created by using a crossover operator.

Crossover is a procedure for exchanging pieces of chromosome data with one another. Crossover allows genes that generate good fitness to be preserved and enlarged in a new generation of the population. Mutation is a genetic operator and it randomly flips the bits of an offspring’s genotype. This is equivalent to perturbing the mated population stochastically. Mutation prevents the population from homogenizing in a particular set of genes such that any gene in a generation has a certain probability (determined by the mutation rate) of being mutated in future generations.

The new population is being mixed up to bring some new information into this set of genes, and this needs to happen in a well-balanced way. Once the new generation is created, the aforementioned steps are repeated until some convergence criteria are satisfied, such as running time and fitness. The overall technique is summarized in a flowchart given in Fig.3.

**Figure 2. Seat suspension with human-body system: Main Simulink model.**

**Figure 3. Design process using GA.**
5. RESULTS AND DISCUSSION

The GA method increases the probability of finding the global optimum solution and avoids convergence to a local minimum which is a drawback of gradient-based methods. Computer simulations are performed for three cases of different weighted factors in order to obtain the required dynamic performance of the proposed design of the seat. The results are generated when excited by an artificial generated step and sinusoidal inputs, respectively.

The optimal vehicle parameters for the present model were determined and the results with GA method were compared with passive model. The design results from the passive and optimal suspensions are tabulated in Table 5. Simulation is performed using driver-seat-car data illustrated in Table 2, for the defined vehicle excitation inputs. The optimal car suspension parameters for the present model were determined by genetic algorithms method, compared with the current passive parameters and tabulated in Table 6.

Table 5. The design results from the GA program

<table>
<thead>
<tr>
<th>Seat suspension setting</th>
<th>Currently used</th>
<th>GA optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sinusoidal</td>
<td>Step</td>
</tr>
<tr>
<td>$K_s$</td>
<td>16000</td>
<td>10039</td>
</tr>
<tr>
<td>$C_s$</td>
<td>980</td>
<td>900</td>
</tr>
</tbody>
</table>

Table 6. RMS percentage improvement results

<table>
<thead>
<tr>
<th>Type</th>
<th>Sinusoidal</th>
<th>Step</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Head</td>
<td>Upper torso</td>
</tr>
<tr>
<td>RMS acceleration</td>
<td>2.093</td>
<td>2.080</td>
</tr>
</tbody>
</table>

In addition, sprung mass was reduced by about 20% and 7% in case of GA suspension as compared with passive suspension for sinusoidal and step excitation inputs, respectively. The reduction of peak values of sprung mass are about 22.5% and 20%, in case of GA suspension as compared with passive suspension for sinusoidal and step excitation inputs, respectively.

Based on the application of genetic algorithms to the optimal design of vehicles suspension, it was found that all parts of human-body acceleration, seat suspension working space, and sprung mass which were reduced by about 21% in case of both sinusoidal and step excitation. The reductions of peak values are more than 19% in case of GA suspension as compared with passive suspension for sinusoidal and step excitation inputs.

6. CONCLUSION

Both the passive and optimal vehicles suspension systems are compared in time domain analyses subjected to sinusoidal and step input. Passive vehicle systems are the most common because they are cheap and effective for most vibration. The optimal design parameters of the suspension systems obtained are $k_s = 10039$ N/m and $c_s = 900$ N.s/m in case of sinusoidal input and $k_s = 10030$ N/m and $c_s = 913$ N.s/m in case of step input, respectively. Step excitation input causes more dangerous on whole body parts (Head, upper torso, lower torso, pelvic, seat, and sprung mass) than those produced by sinusoidal excitation input. Human-body acceleration, seat suspension working space, and sprung mass which were reduced by about 21% in case of both sinusoidal and step excitation. The reductions of peak values of are more that 19% in case of GA suspension as compared with passive suspension for sinusoidal and step excitation inputs.
Figure 4. Sinusoidal acceleration histories: (a) head, (b) upper torso, (c) lower torso, (d) pelvic, (e) seat, and (f) sprung mass.
Figure 5. Sinusoidal displacement histories: (a) head, (b) upper torso, (c) lower torso, (d) pelvic, (e) seat, and (f) sprung mass.
Figure 6 Step acceleration histories: (a) head, (b) upper torso, (c) lower torso, (d) pelvic, (e) seat, and (f) sprung mass.
Figure 7. Step displacement histories: (a) head, (b) upper torso, (c) lower torso, (d) pelvic, (e) seat, and (f) sprung mass.
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