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GT Car's CG height control on a rough road by using series active variable geometry suspension

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ABSTRACT

This paper addresses the vehicle's CG (center of gravity) height control enhancement for the new road vehicle Series Active Variable Geometry Suspension (SAVGS) concept using the PID control technique. Thus, the study utilizes a nonlinear full-car model that accurately represents the dynamics and geometry of a high-performance car with the new double-wishbone active suspension concept. The proposed controller is installed on the nonlinear full-car model, and its performance is examined by the parameters, CG Height and Pitch. In this study, PID is tuned by a Genetic Algorithm, and thus, a robust control system is designed. Finally, the system's robustness is examined through four different simulation configurations, such as different speeds and different road conditions. The vehicle is supposed to be moving to 20 km/h and 100 km/h horizontal speed, and also it is going through Road Classes types C and D. Figures show that this suspension system successfully controls vehicle CG height around a desirable height (0.5m) and does not make harmful impacts on vehicle pitch angle.

1. Introduction

Active vehicle suspensions have attracted great interest in both the academic and industrial communities since the late 1960s; see references [1-3]. One of the main functions of a vehicle suspension is to provide ride comfort and road holding properties as it supports the vehicle body

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and transmits forcing by road excitation between the wheels and the chassis. The suspension design seeks to alleviate the conflict of improving passenger ride comfort and vehicle road holding simultaneously [3]. The primary advantage of active suspensions compared with passive and semi-active alternatives is their ability to resolve this conflict better [4]. However, despite their advanced capabilities, active suspensions have not had a significant impact on the automotive market due to a number of disadvantages related to power requirements, weight, size, and complexity [5].

In terms of control, the works in references [6-10] explored the application of the SAVGS[†] to control vehicle attitude motions and directional responses at low frequency range under longitudinal and lateral accelerations using proportional-integral-derivative (PID) based control methodologies with promising results reported. Further works in references [11] and [12] investigated the control of the SAVGS for higher frequency vehicle dynamics, using *H* control techniques in a quarter-car model setting to provide improved ride comfort and road holding with results that demonstrate the promising prospect of the SAVGS suspension system. SAVGS system is illustrated in Fig. (1) as a double wishbone configuration.

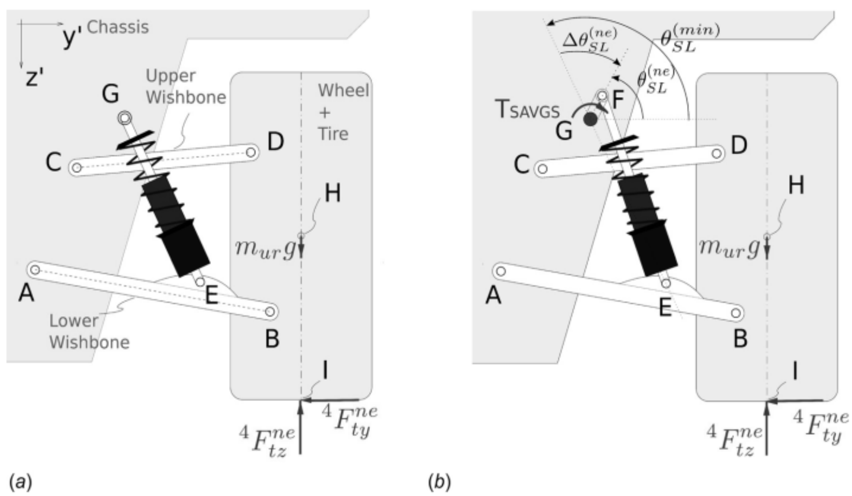

Fig. 1. Double wishbone Suspension configuration of one corner (Right Rear) [7]

In general, the issue of control in active suspensions has attracted attention for many years; Typically, linear control methods such as proportional-integral-derivative control [13], model predictive control [14] and PID control have been developed in several studies and widely applied to the industry [12].

The goal of this paper is to tackle the full-body dynamic of the system with a sinusoidal surface and use PID control methodology with a Genetic Algorithm as PID tuner. There are many methods, including heuristic, meta-heuristic, mathematical programming and etc., that can be used to reach the goal, among which the metaheuristics are at the center of attention and is used in this paper. To solve the problem, in this paper, we have exploited the Genetic Algorithm (GA), a popular evolutionary meta-heuristic method that has many advantages, including

[†] Series Active Variable Geometry Suspension

intrinsic parallelism (exploring the solution space in several directions at once), good performance on problems in which the fitness landscape is complex, capability to deal with several parameters concurrently and no need for knowledge about the problems it is used to solve (because of its meta-heuristic nature) [15].

1.1. Problem statement

The main goal of the paper is to keep the attitude of CG height travel of a small GT[‡] car in sinusoidal surfaces within standard margins; in short, the primary goal is height attitude control. It is important to note that although lowering CG height could lead to better road holding, the aim of this work is not lowering but to keep the CG height at around the natural amount as a control method not just better road holding at certain maneuvers, natural amount of CG height, in this case, is 0.5m. In the following, it will be explained that what exactly is the attitude of CG of a car and also what are the GT parameters and what maneuver is going to be used in this paper.

In order to control the height of vehicle, first, the vector on which height movements of vehicle occur needs to be defined; Vector Z in Fig. (2) shows the positive direction of these movements and is that vector. In this paper, the magnitude of the height movements of vehicle needs to be kept at around 0.5m; it can be kept at any desirable value, which in this paper is 0.5m, according to the given references [16-18]. W# is the index of wheels (front left & right=1&2, rear left & right=3&4). After that, vehicle parameters should be introduced. The vehicle in this study is a GT car which is normally small and not very highly weighted. Table 1 illustrates the vehicle parameters.

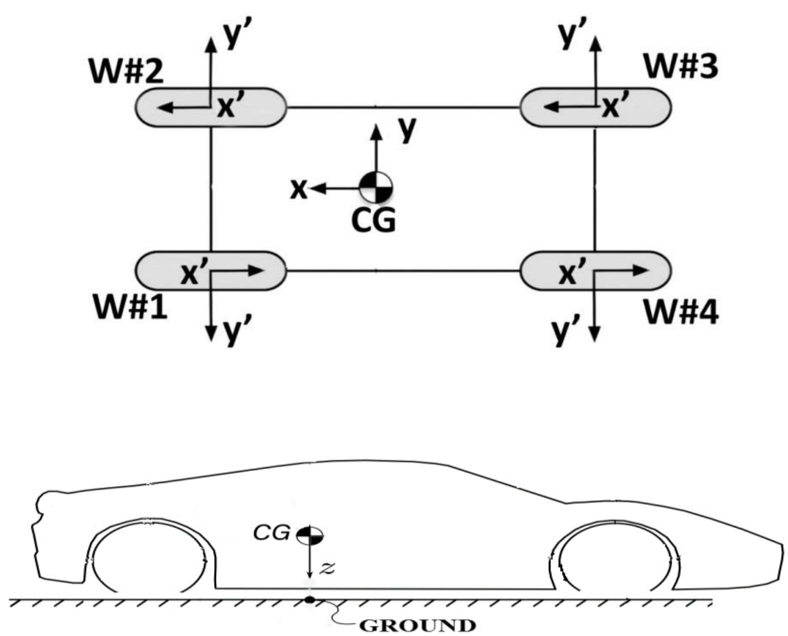

Fig. 2. Vector z and other important vectors of the GT [9]

‡ Grand Tourer

Table 1. GT Parameters

Parameter	Units	Axle	Value
Total Mass/Sprung Mass	Kg	-	1525/1325
Wheelbase/CG Height	mm	-	2600/450
Weight Distribution	%	F/R	57/43
Spring Stiffness	N/mm	F/R	92/158
Tire Stiffness	N/mm	F&R	275
Wheel Radius	mm	-	341

1.2. Simulation

The details of the maneuver should be discussed; The vehicle is heading towards two symmetrical sinusoidal roads (Classes C and D [19]) with two different velocities, 100 km/h and 20 km/h. The objective is to keep the height of the CG from the ground around 0.5m, but the symmetrical sinusoidal road is going to make some disturbances on the height of the vehicle; the whole maneuver takes 20 seconds to be completed for each speed and road type. GT cars, such as the one studied in the present work, are normally traveling on road surfaces of good quality (type A), although, the road in this study is a poor-quality road (type C). It is essential to note that the test has a time delay system so that all of the wheels would go under disturbance, same as in [16, 18-22].

After having the system and the maneuvers modeled, which will be illustrated in the next section, the height response of the vehicle using passive suspension will be calculated, which can be seen in Fig. (3). It can be seen that the CG point is traveling upward and downward by a magnitude of around 0.25m which is undesirable. In this paper, the desired range for CG travelling is around (0.0m to 0.8m]. By this logic, passive suspension cannot fulfill the objective; therefore, it is desired to use SAVGS as the suspension system and examine the results and effects of this system on the CG height travel [23, 24].

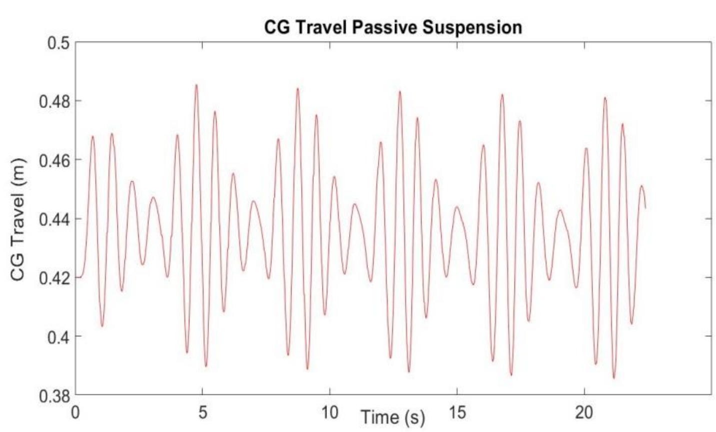

Fig. 3. CG Travel using Passive Suspension

1.3. Paper structure

Based on previous research in the field of SAVGS systems, PID controller never was applied to control CG height and keep it in determined margins. Additionally, this suspension system had not been tested on rough roads and this paper aims to cover that. Finally, the Genetic Algorithm never was used to tune PID controller of SAVGS systems which again, this paper intends to do. To sum up, contributions of this paper can be summarized in three parts:

- Using a simple controller (PID controller) on a vehicle equipped with SAVGS to control CG Height for the first time
- Studying SAVGS on rough surfaces for the first time
- Employing, customizing and tuning an evolutionary meta-heuristic algorithm (GA) to optimize PID controller coefficients for rough surfaces

Also, the full list of parameters used in this work can be found in Table 2.

Table 2. List of Parameters

Parameter	Name	Parameter	Name
z	CG Height Travel Vector	$F_{tz}/F_{ty'}$	Tire Forces in Direction of z/y'
$\boldsymbol{g}$	Earth Gravitational Acceleration	d	First Differential
$\boldsymbol{a_{y'}}$	Lateral Acceleration of a Wheel	m_u	Unsprung Mass
$\boldsymbol{F_{SD}}$	Spring Damper Forces	l_{SD}	Spring Damper Length
$\boldsymbol{x_{ss}}$	State Space Variables	$u_{ss}/\ y_{ss}$	State Space Inputs/Outputs
V	Horizontal Velocity	$\dot{\theta}^*_{SL1}$	Single Link Reference Angular Velocity of Wheel #1-4
$\boldsymbol{z_{dr1-4}}$	Vertical Movements of Wheel #1-4	T_r/T_p	Vehicle Roll/Pitch Acceleration Torque
$\mathbf{K_{p-i-d}}$	Coefficient of Proportional-Integral Derivative of PID	K_u/T_u	Ziegler-Nichols Coefficients
RMS	Root Mean Square	$H/\ H^*$	Optimization State/Reference Amount

2. Full car modeling

2.1. Dynamic modeling

In the following, the GT is going under modelling. First, it is needed to formulate the governing equations of the dynamic system. The suspension system for one corner of the car was illustrated in Fig. (1). The governing equation for the SAVGS system in this car can be seen in Eq. (1). Which is needed to be represented in the state-space form, as in Eq. (2). The reason for using the state-space form is to simplify the process of PID designing in MATLAB/SIMULINK, according to Fig. (4). It will be clarified that one of the outputs, which is vehicle CG height movements, is fed to PID controller unit so it can control four of the inputs, which are SAVGS single link reference angle velocities.

$$F_{tz} + F_{ty'} \times \frac{dy'_I}{dz_I} + m_u\left(g\frac{dz_H}{dz_I} + a_{y'}\frac{dy'_H}{dz_I}\right) + F_{SD}\frac{dl_{SD}}{dz_I} = 0 \tag{1}$$

$$\begin{cases} \dot{x}_{ss} = Ax_{ss} + Bu_{ss} \\ y_{ss} = Cx_{ss} + Du_{ss} \end{cases} \tag{2}$$

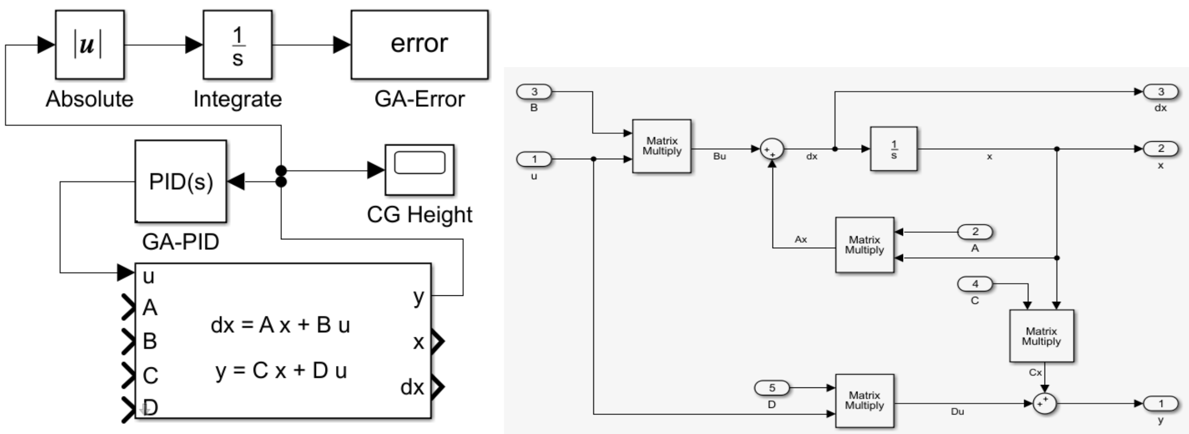

Fig. 4. Proposed Modeling System

where F_{tz} and $F_{ty'}$ are the vertical tire forces at any given corner of the car, m_u is the unsprung mass, points H and I can be found in Fig. (1), and F_{SD} is the spring damper force.

Also:

$$u_{ss} = \left[T_p, T_r, z_{dr1}, z_{dr2}, z_{dr3}, z_{dr4}, \dot{\theta}^*_{SL1}, \dot{\theta}^*_{SL2}, \dot{\theta}^*_{SL3}, \dot{\theta}^*_{SL4}\right]^T \tag{3}$$

Two of the parameters that make the model more complex are T_p *and* T_r which are vehicle Pitching Torque on sprung mass and Rolling Torque on sprung mass, respectively. Values of these two parameters change through time and are dependent on the other inputs of the system as well. Also, the state-space matrices (A, B, C, D) can be found in [8], since the vehicle in this paper is identical to the vehicle in [8] to compare controllers and change some of the inputs, using the same state-space matrices satisfy these objectives. The dynamic built in MATLAB/SIMULINK model can be seen in Fig. (5).

Four out of ten inputs are Suspension systems single link reference velocity for each wheel which are produced by the controller unit. As it can be seen in Eq. (3), the model takes vehicle torques and road movements and single link reference velocities (whose are desired single link velocities for better performance) as inputs. These values should be produced by the system. Vehicle pitch and roll torques and single link reference velocities are inner system parameters, but vertical road movement are outer system production. Thus, roads should be generated. The produced roads Class D (Velocity=27.7 m/s and 5.5 m/s) can be seen in Fig. (6). Also, the produced roads Class C (Velocity=27.7 m/s and 5.5 m/s) can be seen in Fig. (7).

As discussed before, two types of road were used for the simulation, which are road types C and D. Also, the simulation was run at two different speeds, 100 km/h and 20 km/h. Each road is the sum of three sinusoidal roads which were produced according to ISO 8608 [19]. These values make four out of ten of the inputs which are vertical road displacement for each wheel. It is important to mention that the simulation time is 20 seconds [25].

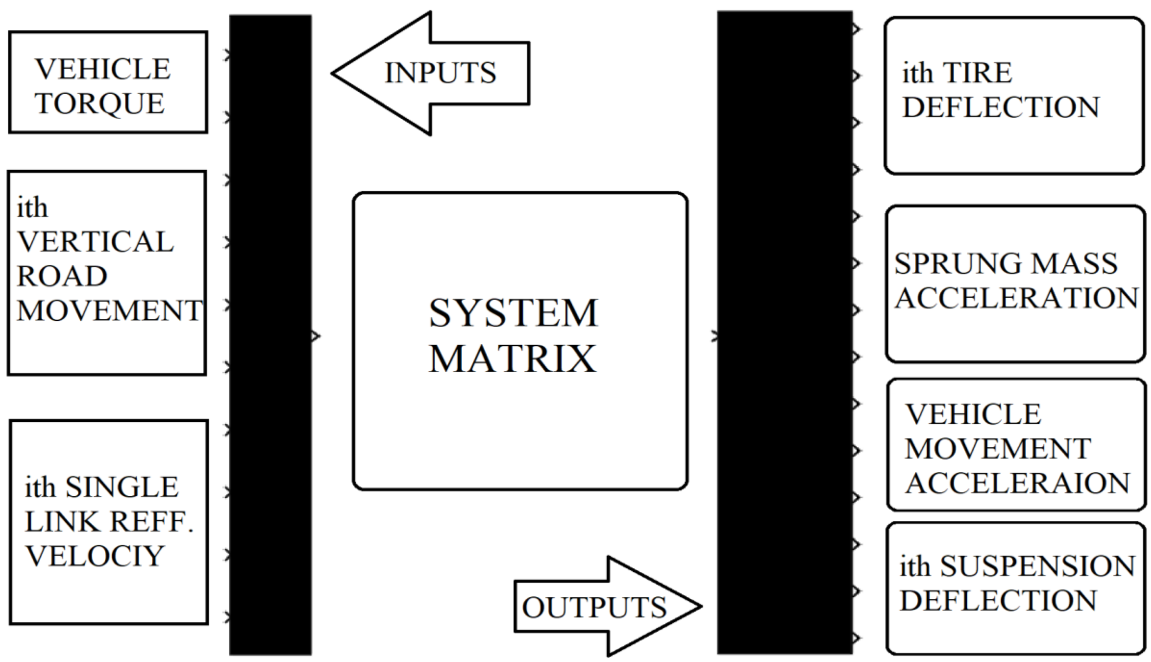

Fig. 5. CG Dynamic built in MATLAB/SIMULINK Model

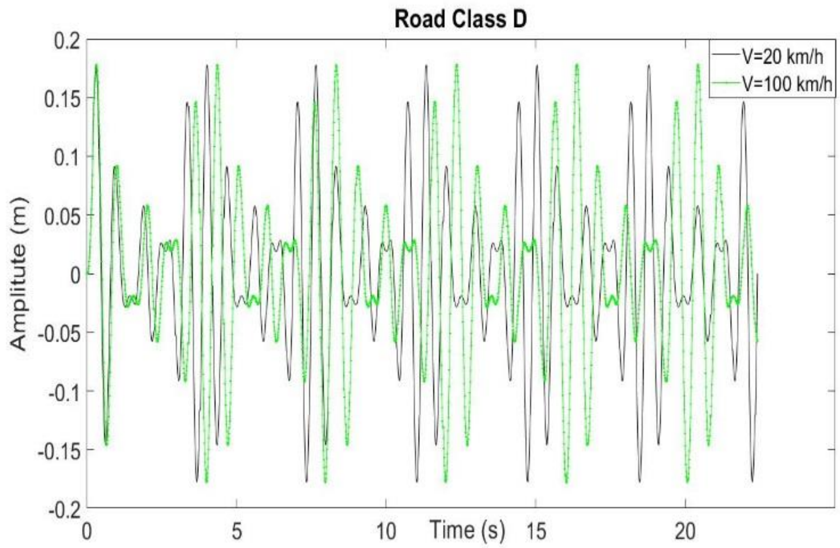

Fig. 6. Road Class D

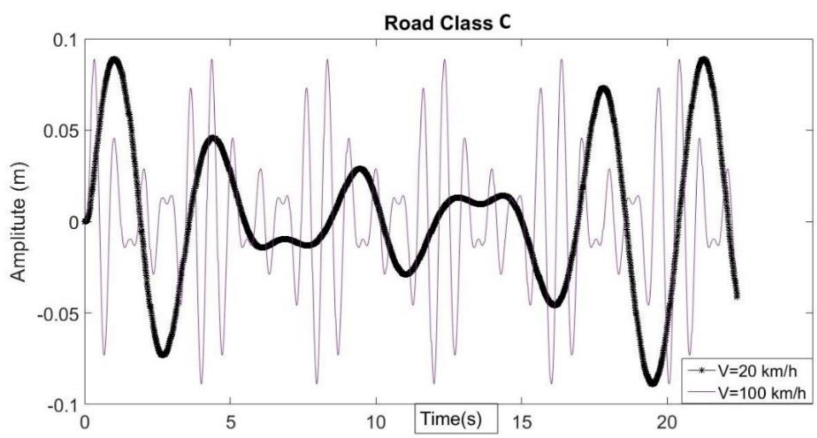

Fig. 7. Road Class C

It can be seen that, on both roads, the maximum amplitude of the bump is equal for both velocities, but the frequency of the wave is different [26]. Road Class C with 20 km/h has a smooth frequency, but the same road has a harsher frequency with 100 km/h, as can be seen in Fig. (7). The same rule is also correct for road Class D, but since this type of road has a lot more harshness than road type C, even with 20 km/h has more frequency than road Class C with 100 km/h. It is worthy mentioning that road Class D with 100 km/h is the roughest road that the vehicle in this paper is going through.

So far, system inputs have been illustrated, but the system outputs are important too. As it can be seen in Fig. (5), the system has 15 outputs, the first four show tire deflections for each wheel; the second four show the sprung mass acceleration for each suspension of each wheel, and the next three are more important to us in this paper, vertical sprung mass center acceleration shows the CG movement in vertical direction which is one of the most important parameters of Ride

Comfort. Sprung mass pitch acceleration is the next important output, which shows the vehicle pitching acceleration of the CG which is another Ride Comfort parameter [27]. Sprung mass roll acceleration is the same thing only for vehicle roll. The last four of the outputs are suspension deflection for each wheel [28].

3. Controller and optimization

To control the system behavior, PID controller was chose to keep the system parameters within the acceptable limits. PID is simple, accurate and robust, the input of the PID block is the error which is desired to be zero [14]. This error is the difference between the desired height of the CG and real time height of the CG. Output of PID block as said before is single link reference velocity for each suspension on each wheel. PID block inputs and outputs are simplified in Fig. (8).

PID input can be seen in Fig. (9). PID has to make the input (error) settle around zero and for now has a mean amplitude of 6 cm [29, 30]. As it usknown, PID controller should be tuned for P, I and D coefficients. One of the best ways to find these coefficients is to use the Zeigler-Nichols method [31]. To start the tuning process, Zeigler-Nichols method must be followed in order to find the PID initial coefficients [32, 33]. Table 3 is gathered so it can illustrate how the Ziegler-Nichols coefficients were calculated; also it includes the results.

Table 3. Ziegler-Nichols Coefficients [33]

Parameter	K_p	K_i	K_d
Formula	0.6 K_u	1.2 K_u/T_u	$3\ K_u\ T_u/40$
Value	-78	-260	-5.85

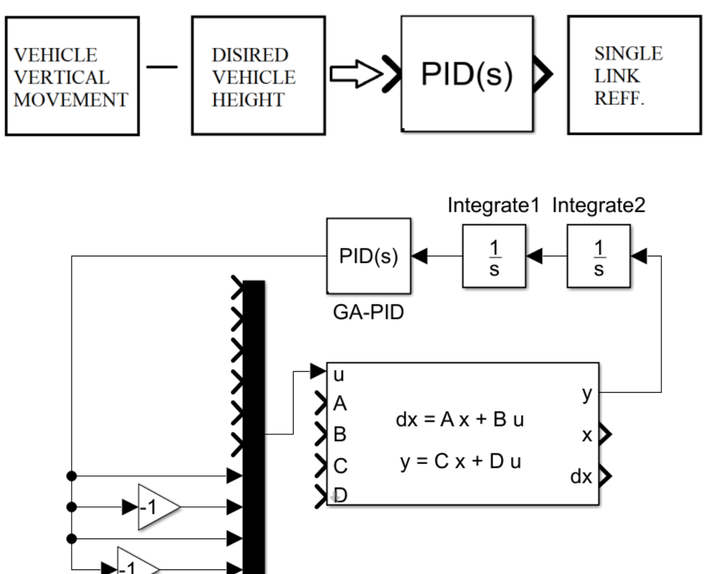

Fig. 8. PID Block Inputs and Outputs

Also, $\mathbf{K_u}$ *and* $\mathbf{T_u}$ should be found by trial and error method, which are -130 and 0.6, respectively [33].

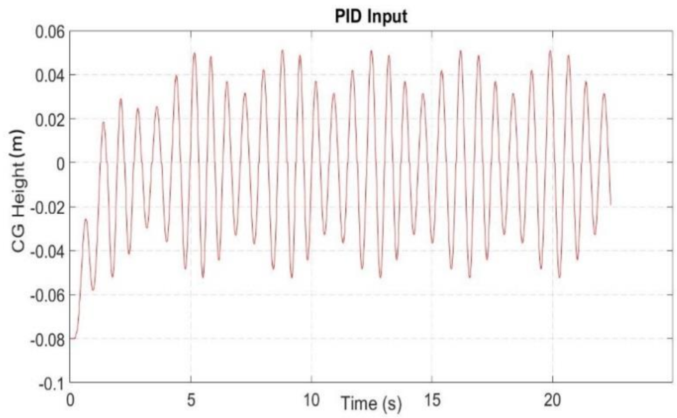

Fig. 9. PID Block Inputs and Outputs

Although there are various types of evolutionary algorithms such as ACO, PSO and SA [15] to tune PID coefficients, according to the nature of our problem, the Genetic Algorithm (GA) [34] is selected as an effective heuristic for optimizing the coefficients of PID controller.

Table 4. GA Parameters

Parameter	Amount	Parameter	Amount
Population Type	Double Vector (40 & 50)	Creation Function	Uniform
Fitness Function	Top & Rank	Selection Function	Roulette
Crossover Fraction	0.4-0.8	Mutation	Uniform
Migration	0	Fitness Limit	0
Function Tolerance	1E-6	Mutation Rate	0.01
Initial Population	0	Mutation Function	Constraint Dep.

The Genetic Algorithm's main equation is Eq. (4), which means that the algorithm has one constraint (H) and three parameters (K_p, K_i, K_d).

$$Minimize \left\{\int \left(H(K_p, K_i, K_d) - H^*\right)\right\} \quad (4)$$

It is necessary to mention that the objective of the optimization is to minimize the integration of the PID block input. The Genetic Algorithm results after 92 iterations for PID Controller were [-47.4, 0.104, 0.0554] for P, I and D respectively, that led to RMS=0.0231 which is around 20 percent improvement in comparison with non-optimized coefficients. Genetic Algorithm parameters can be found on Table (4).

4. Results

Results are in four different simulation conditions since the simulation has four different conditions.

4.1 V=100km/h, Road Class C

First, the Vehicle is cruising at a 100 km/h horizontal velocity on a symmetrical road class C, vehicle CG travel response to this input can be seen in Fig. (10), it can be seen that the height of the vehicle is reached desired amount (0.5m) after around 2 seconds, it stays on a 4cm margin from CG desired height; also the RMS of error from desired CG height (0.5m) for passive response is 0.0746 and the RMS for the active PID response is 0.0195, which means 73% improvement.

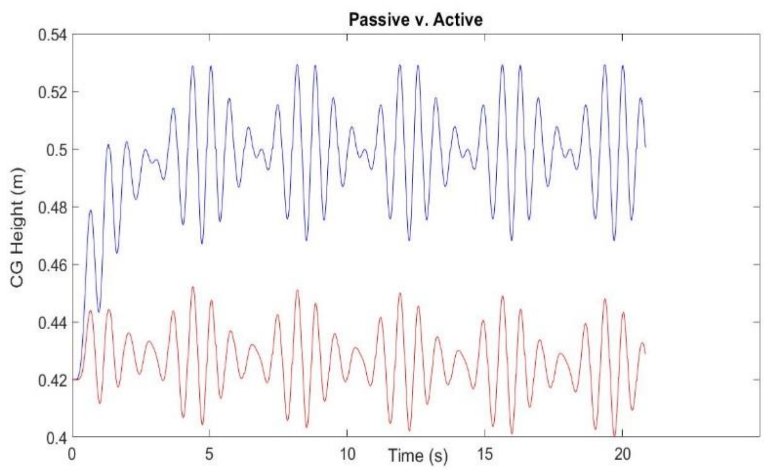

Fig. 10. Vehicle Height Response. V=100km/h, Road Class C. PID Active=Blue. Passive=Red.

Also, vehicle pitch angle behavior which can be seen in Fig. (11) is provided and it shows that vehicle pitch angle increase won't exceed one degree using PID Controller.

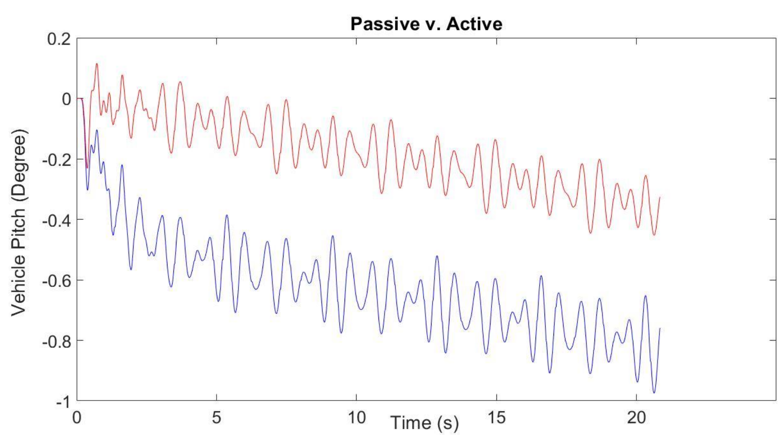

Fig. 11. Vehicle Pitch Response. V=100km/h, Road Class C. PID Active=Blue. Passive=Red.

4.2. V=100km/h, Road Class D

This simulation is the toughest situation that GT is going through in this paper, Vehicle is cruising at a 100 km/h horizontal velocity on a symmetrical road class D, vehicle CG travel response to this input can be seen in Fig. (12), it can be seen that the height of the vehicle is reached to desired amount after less than 1 second, and it stays on a 10cm margin from CG desired height (0.5m), also the RMS of error from desired CG height for passive response is 0.0682 and the RMS for the active PID response is 0.0306, which is 55% improvement.

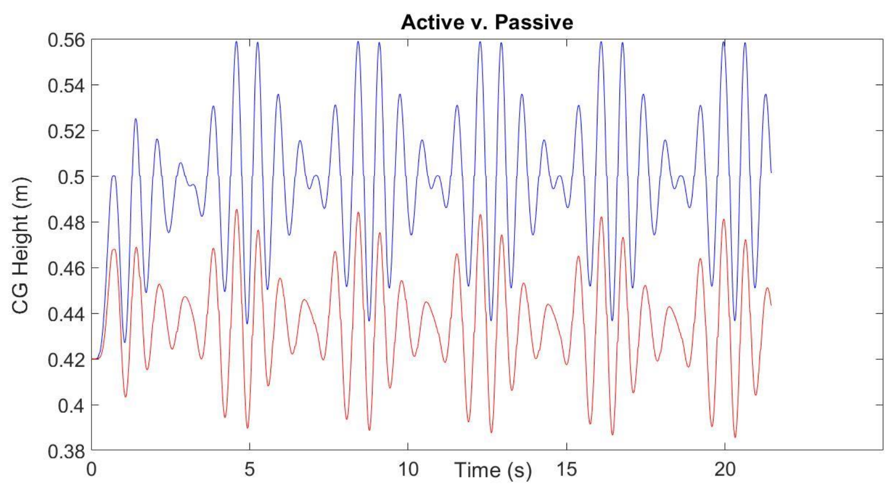

Fig. 12. Vehicle Height Response. V=100km/h, Road Class D. PID Active=Blue. Passive=Red.

Also, vehicle pitch angle behavior which can be seen in Fig. (13) is provided and it shows that the vehicle pitch angle increase will not exceed one degree using PID Controller.

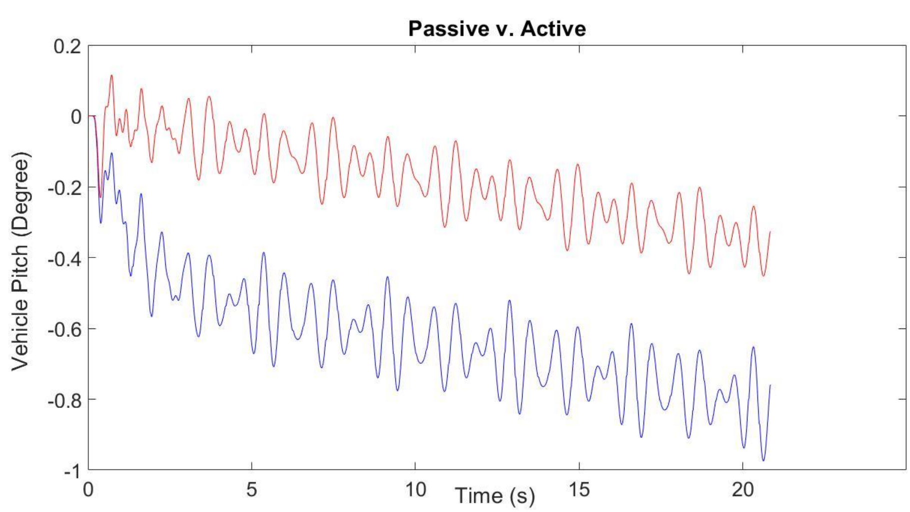

Fig. 13. Vehicle Pitch Response. V=100km/h, Road Class D. PID Active=Blue. Passive=Red

4.3 V=20km/h, Road Class C

In this simulation part, vehicle is cruising at 20 km/h horizontal velocity on a symmetrical road class C, vehicle CG travel response to this input can be seen in Fig. (14), it can be seen that the height of the vehicle is reached to desired amount after less than 2 seconds, and it stays on a 4cm margin from CG desired height, also RMS of the error from desired CG height (0.5m) for passive response is 0.0425 and RMS for the active PID response is 0.0183, which is 56% improvement.

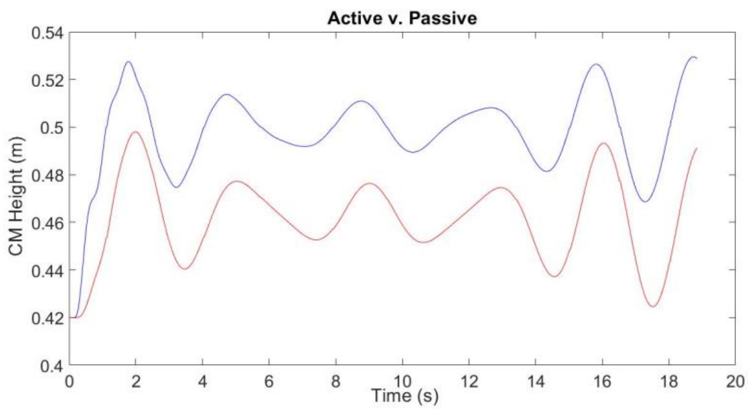

Fig. 14. Vehicle Height Response. V=20km/h, Road Class C. PID Active=Blue. Passive=Red.

Also, vehicle pitch angle behavior which can be seen in Fig. (15) is provided and it shows that vehicle pitch angle increase will not exceed 1.5 degrees using PID Controller.

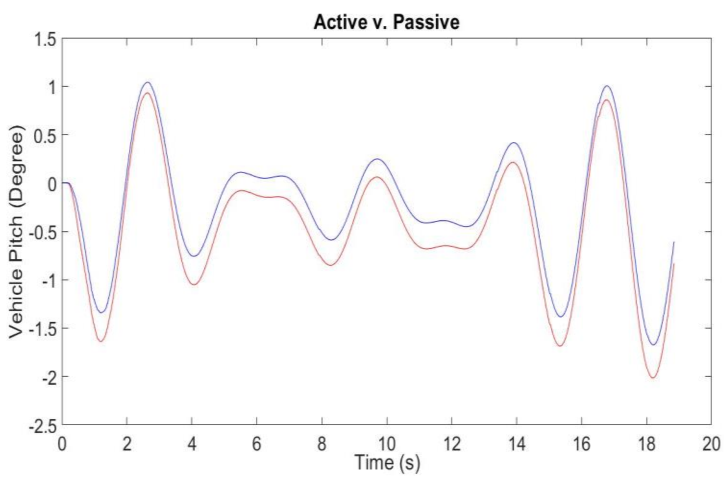

Fig. 15. Vehicle Pitch Response. V=20km/h, Road Class C. PID Active=Blue. Passive=Red.

4.4. V=20km/h, Road Class D

In this simulation part, vehicle is cruising at 20 km/h horizontal velocity on a symmetrical road class D, vehicle CG travel response to this input can be seen in Fig. (16), it can be seen that the height of the vehicle is reached to desired amount after less than 2 seconds and it stays on a

10cm margin from CG desired height and also RMS of error from desired CG height (0.5m) for passive response is 0.0424 and RMS for the active PID response is 0.0309, which is 27% improvement.

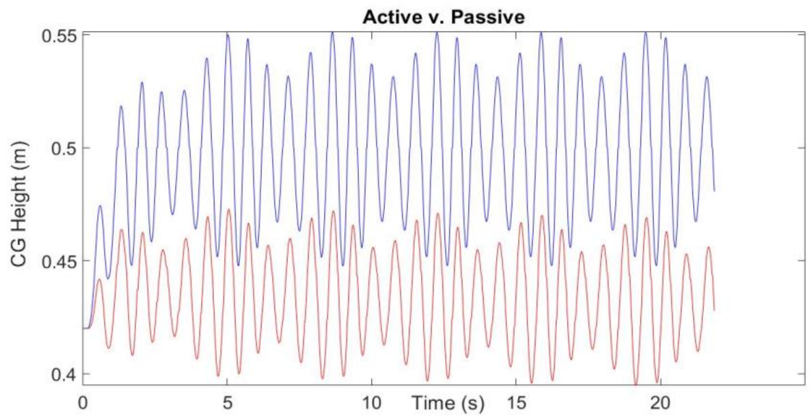

Fig. 16. Vehicle Height Response. V=20km/h, Road Class D. PID Active=Blue. Passive=Red.

Also, vehicle behavior pitch which can be seen in Fig. (17), is provided. it shows us that vehicle pitch angle increasement won't exceed degree using PID Controller.

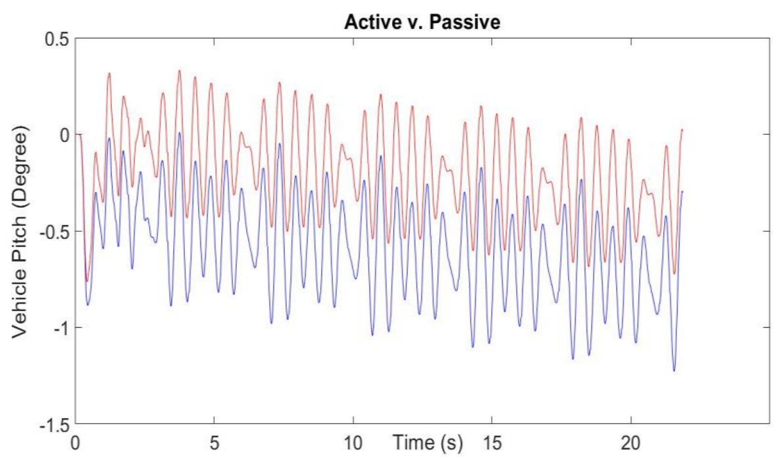

Fig. 17. Vehicle Pitch Response. V=20km/h, Road Class D. PID Active=Blue. Passive=Red.

5. Conclusion

SAVGS suspension system on a GT car was tested in this paper for controlling the CG height of the vehicle by using PID controller and Genetic Algorithm as PID tuner on sinusoidal roads classes C and D. Vehicle and roads were modeled on MATLAB/SIMULINK and test simulations also were simulated on this software. This suspension system was proved to be instrumental for keeping the height of the vehicle in desirable margins and with horizontal speeds of 100 km/h and 20 km/h.

More precisely, Active suspension system improvements in comparison with passive suspension on road class C were greater than road class D; also as the vehicle speeds up, improvements in the behavior of the vehicle become greater. It can be seen that, the greatest improvement occurred on road class type C with 100 km/h horizontal speed which is 73% improvement in height control. On the other hand, as the road becomes harsher and vehicle speed becomes slower, active suspension system improvements on height control become less. That is the reason that improvements on road class D with 20 km/h is 27% (nearly one-third in comparison with road class type C). To sum up, although SAVGS system proved to be useful and this system acts instrumental in vehicle height control, but the performance of it is when the vehicle speed becomes greater and the road becomes smoother.

In this work, the use of PID controller for SAVGS system was tested and resulted in up to 73% improvement on Road types C and D. The Genetic Algorithm was used to Tune PID controller and improved PID controller for controlling vehicle CG height up to 11%. At last, it is proven that the method described in this paper could be instrumental as a means to control vehicle CG height using PID controller.

In future works, it is recommended to test this suspension system for different goals of ride comfort and road holding, also this system can work on a heavier vehicle. It is also recommended to use a multi-objective controller and optimization.

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