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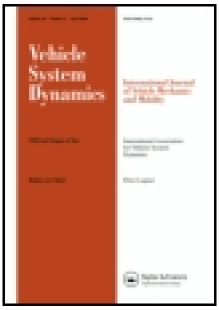

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An investigation into the effect of suspension configurations on the performance of tracked vehicles traversing bump terrains

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This is a theoretical investigation into the effect of various suspension configurations on a tracked vehicle performance over bump terrains. The model developed is validated using published experimental data of the modal characteristics of the vehicle. The desired performance is based on ride comfort via the mixed objective function (MOF), which combines the crest factor of bounce acceleration, bounce displacement, angular acceleration, and pitch angle. The optimisation process involves evaluating the MOF for different numbers and locations of dampers and under different rigid bump road conditions and speeds. The system responses of the selected suspension configurations in the time and frequency domains are compared against the undamped suspension. The results show that the suspension configurations have a significant effect on the vehicle mobility over bump road profiles. For a five-road–wheel half model of a tracked vehicle, the maximum number of dampers to use for ride comfort over these road bumps is three with the dampers located at wheel positions 1, 2 and 5. This confirms the current practice for many tracked vehicles with 10 road wheels. However, it is further shown that the suspension fitted with two dampers at the extreme road wheels offer the best performance over various rigid bump terrains.

Keywords: tracked vehicle; vehicle suspension system; off-road vehicle suspension configurations; half vehicle suspension model; bump terrains; ride comfort

1. Introduction

Tracked vehicles are subjected to severe excitations while traversing over rough terrains. These excitations have a significant effect on the ride comfort and safety of the driver and crew. High-mobility tracked vehicles such as main battle tanks and armoured personnel carriers (APC) are intended to traverse over smooth and uneven terrains. Prolonged exposure to such vibration environment causes vast limitations to the vehicle mobility and adversely affects the crew's performance.[1] Consequently, the maximum traverse speed is constrained by terrain profile and suspension capability to withstand the road-induced vibrations.[2] A crucial mechanism that minimises road-induced vibrations and therefore improves vehicle comfort is the suspension system. Generally, a tracked vehicle suspension system consists of elastic and damping elements, i.e. torsion bars and dampers, which connect the hull body to the road wheels.

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Although off-road vehicles vary extensively in shape, size, and physical type, they share several common characteristics in their suspension configurations. From the damper configurations point of view, there are various configurations (numbers and locations of dampers) used in different off-road vehicles based on the vehicle type and purpose. All these suspension systems share the damper locations, but vary in the number of dampers fitted to the suspension. There are two configurations of dampers used in defence-related tracked vehicles, namely two dampers configurations for infantry fighting vehicles which have large moment arms from the road wheels to the vehicle centre of gravity (CG), three dampers configurations for APC, which have smaller moment arms from the road wheels to the vehicle CG. The lengths of the moment arms affect the magnitude of the damping and elastic restoring forces generated. But which of these configurations is ideal?

Further analysis is required to examine the suspension performance with different configurations of dampers under different road conditions. The question arises as to why off-road-tracked vehicles suspensions exploit two or three dampers only? What are the best locations of dampers that improve the suspension characteristics? In addition, what will happen to the vehicle performance if more than three dampers are used? Moreover, what is the influence of using dampers at all wheels on the suspension reaction when traversing over terrains with various roughness and speeds? Furthermore, what are the optimum numbers and locations of dampers that should be used to ensure good isolation from road-induced vibration? Several studies have been conducted on tracked vehicle ride comfort and its improvement. Norms that determine the acceptable limits of comfort have been listed in various studies such as BS 6841 [3] and [4,5]. Normally, suspension performance can be evaluated in terms of ride comfort, road handling and stability. These three factors are in conflict with each other while a vehicle is in operation.[6] The paper concentrates on the effect of suspension configurations on ride comfort only. The suspension index related to the vehicle comfort is influenced by the road-induced vibration and its effect on the driver and crew. In fact the terrain profiles play an important role affecting the vehicle mobility as well as the comfort situation. When the vehicle crosses a paved terrain (smooth), there is no significant outcome on vehicle mobility. However, rough terrains impose high vibration levels to the suspension and limit the traversing vehicle speeds.[7]

In previous suspension optimisation studies, there are several weighted functions which have been used in conjunction for suspension performance evaluation. In the literature, various indices such as sprung mass acceleration, suspension travel and wheel deflection are commonly used for suspension performance evaluation.[8] In this work the performance index is based on a combination of the crest factor (CF), bounce acceleration (BA), bounce displacement (BD), angular acceleration (AA) and pitch angle (PA). The CF is defined as the relation between the peak amplitude of the signal to the root mean square (r.m.s.) value. This factor offers a quick and important predictor of how much impact occurs during time periods.[9] The optimal suspension settings are determined based on the simulation of the suspension model using the Matlab/Simulink software. A better understanding of the effect of the suspension performance on the vehicle ride comfort is accomplished through comprehensive analyses of suspension design parameters using computer simulation models. These models are commonly employed to quantify the influence of the suggested parameters before the final design process and testing. Some of the models have been used to study the tracked vehicle performance with varying complexities.[10–14] A few of these mathematical models have been validated against field tests with some apparent success.[11,15,16] Most of the literature on the evaluation of tracked vehicle performance is based on the influence of the torsion bars stiffness and/or assembly angle,[15,16] the number of road wheels [15] and damping coefficient of shock absorbers on the vehicle dynamic characteristics.[2]

The paper presents the application of a tracked vehicle simulation model for the assessment of the effect of the suspension configurations (numbers and locations of dampers) on the tracked vehicle ride performance. The model is validated using published experimental data for the undamped free and forced vibration characteristics of the vehicle. The suspension performance is evaluated over various bump terrain profiles referred to as shallow, medium and sharp bump terrains at three different vehicle speeds. The terrain profiles and speed ranges are selected to widely cover the field operational conditions. The results are presented and compared for different combined weighted function (in terms of CF) and for different roads.

2. Half model for the suspension system of a tracked vehicle

As stated in the introduction, a variety of mathematical dynamic models for full or half tracked vehicle suspension models have been developed for the evaluation of the tracked vehicle performance. However, a two-dimensional model of a tracked vehicle is found to be sufficient for detailed analysis of the suspension dynamics and associated shock and vibration environment of the vehicle.[1] Also, the models can be classified broadly into two categories, namely: (i) full, complete models that include the track–terrain interaction effects [1,2] and (ii) simplified models that exclude the track–terrain interaction effects.[10–14] Because the focus of this paper is on the effect of various suspension configurations on a tracked vehicle performance rather than on the influence of the terrain surface characteristics, the simplified model is adopted for the present work.

To obtain a close insight of the APC M113-tracked vehicle suspension system, a description of an undercarriage, which is shown in Figure 1 as an example, is provided as follows. Such a system consists of two major parts, which are the track drive system and the suspension system. The former system consists of two driving sprockets located in the front and two idler wheels in the rear and all enclosed by the tracks. In the subsequent system, there are five wheels connecting the vehicle hull with the tracks throughout five-wheel arms. Each wheel arm is anchored to the hull via a torsion bar which is located at the bottom of the hull. It should be noted that three shock absorbers per side are fitted in the suspension system for this particular vehicle. These absorbers are allocated to the first, second and fifth wheel stations.

For the purpose of this study, an in-plane dynamic model of a typical off-road-tracked vehicle, M113-A3, traversing a rigid (non-deformable) terrain, is developed in the Matlab/Simulink environment. The model has $N + 2$ degrees-of-freedom (DOF); N is the

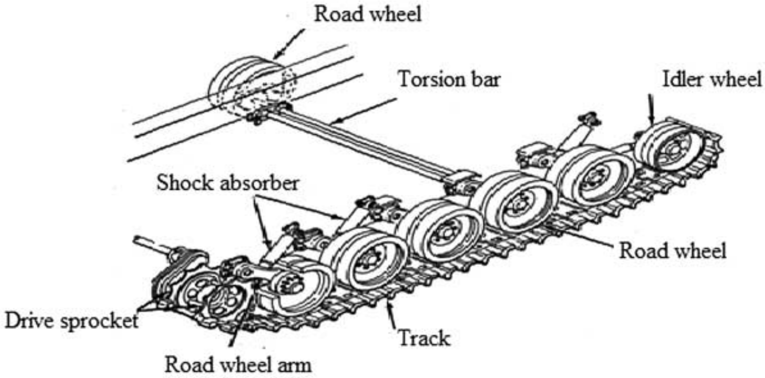

Figure 1. Undercarriage of APC M113.[1]

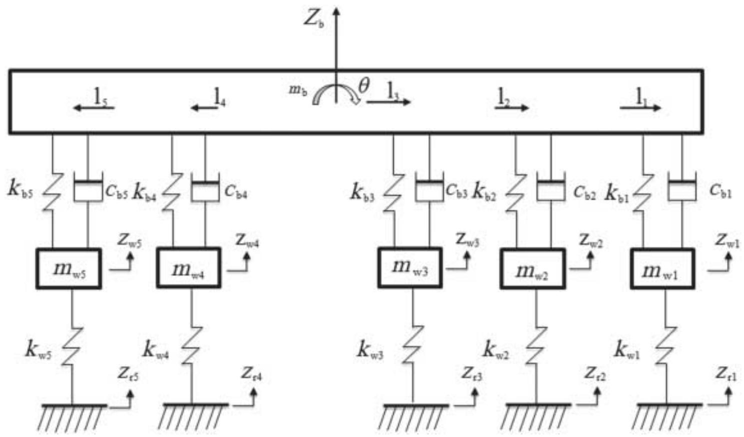

Figure 2. Half tracked vehicle suspension model.

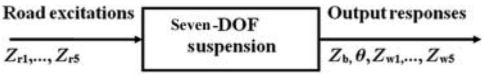

Figure 3. Block diagram of model inputs and outputs parameters.

number of road wheels per side. Figure 2 illustrates a half model of the M113 wherein half of the hull mass is supported by five road wheels. The model is two dimensional with asymmetry about a vertical axis passing through the CG of the hull mass. The model has seven-DOF, two-DOF (vertical bounce and PA) associated with hull mass and five-DOF (vertical bounce) related to the five road wheels. The suspension system is modelled as a parallel combination of springs and dampers, wherein the wheels' stiffness is represented by equivalent spring stiffness.

It is noted that the actual suspension of the M113-A3 has only three hydraulic dampers attached to wheel numbers 1, 2 and 5. However, there are five dampers shown in the model for the purpose of investigation. The differential equations governing the suspension model are expressed based on Newton's Second Law of Motion. Also, in the development of the model, the following assumptions are made:

(1) The body mass element is assumed to be a rigid body.
(2) The torsion bars are represented by independent linear springs.
(3) The shock absorbers represent the damping elements which dissipate the energy and have constant damping coefficients;
(4) The road wheel tyres are assumed to be much more rigid than the torsion bars.
(5) The terrain is rigid (i.e. non-deformable).
(6) The effect of the terrain on the dynamics of the suspension is not considered.

Based on these assumptions, the half suspension system of the tracked vehicle model can be developed. The hull bounce, pitch and the wheel bounce motions are expressed in the following equations and the data provided for simulation are taken from [1,17,18] and listed in Table 1. Also, Figure 3 shows the input excitations to the model in addition to the outputs degrees of freedom. It should be noted that the following equations of motion are not the same as those in [1,19].

Table 1. Half model suspension parameters for off-road vehicle [1–3].

Description	Symbol	values	Description	Symbol	values
Body mass (kg)	m_b	5109	First wheel centre[a] (m)	l_1	1.35
Body inertia (kg m^2)	I_y	12,856	Second wheel centre (m)	l_2	0.69
Suspension stiffness (N/m)	$k_{\mathrm{b}i}$	104,000	Third wheel centre (m)	l_3	0.02
Damping coefficient (N s/m)	$c_{\mathrm{b}i}$	22,520	Fourth wheel centre (m)	l_4	−0.66[b]
Wheel mass (kg)	$m_{\mathrm{w}i}$	113.5	Fifth wheel centre (m)	l_5	−1.32
Wheel stiffness (N/m)	$k_{\mathrm{w}i}$	613,000	Angular displacement	θ	NA
Body vertical displacement	Z_b	NA			

Notes: N.A, not applicable. Subscripts meaning: b, body; y, lateral axis; w; wheel.
[a] The horizontal distance between the hull C.G and the road wheel centre.
[b] Negative values denote that the distance is measured behind of the body centre.

Bounce motion of the hull:

$$m_\mathrm{b}\ddot{z}_\mathrm{b} + \sum_{i=1}^{5} c_{\mathrm{b}i}(\dot{z}_\mathrm{b} + \mathrm{l}_i\dot{\theta} - \dot{z}_{\mathrm{w}i}) + \sum_{i=1}^{5} k_{\mathrm{b}i}(z_\mathrm{b} + \mathrm{l}_i\theta - z_{\mathrm{w}i}) = 0. \tag{1}$$

Pitch motion of the hull:

$$I_y\ddot{\theta} + \sum_{i=1}^{5} c_{\mathrm{b}i}(\dot{z}_\mathrm{b} + \mathrm{l}_i\dot{\theta} - \dot{z}_{\mathrm{w}i})\mathrm{l}_i + \sum_{i=1}^{5} k_{\mathrm{b}i}(z_\mathrm{b} + l_i\theta - z_{\mathrm{w}i})l_i = 0. \tag{2}$$

Bounce of the ith road wheel:

$$m_{\mathrm{w}i}\ddot{z}_{\mathrm{w}i} - c_{\mathrm{b}i}(\dot{z}_\mathrm{b} + \mathrm{l}_i\dot{\theta} - \dot{z}_{\mathrm{w}i}) - k_{\mathrm{b}i}(z_\mathrm{b} + \mathrm{l}_i\theta - z_{\mathrm{w}i}) + k_{\mathrm{w}i}(z_{\mathrm{w}i} - z_{\mathrm{r}i}) = 0 \tag{3}$$

for $i = 1, \ldots, 5$.

All the variables and parameters in these equations are defined in Table 1, which also states their typical values used in the simulations.

3. Evaluation of damped and undamped-tracked vehicle performance

3.1. *Description of different suspension configurations*

The influence of the different suspension configurations on the tracked vehicle response is investigated through a series of simulations. Therefore, a typical set of M113-A3-tracked vehicle design parameters is introduced as an example in this investigation. The suspension system of such a vehicle consists of five road wheels with five torsion bars per side. Five suspension configurations with different numbers and locations of dampers are used in this study to assess the effect of suspension settings on the vehicle performance. In addition, the undamped suspension is used for comparisons between all suspension configurations. Table 2 summarises the proposed suspension configurations that have been used during this study. The table includes five suspension configurations in addition to the undamped suspension; these configurations are denoted as S0, S1, S2, S3, S4 and S5 as shown in Table 2. Configuration S0 includes no dampers, S1 contains 1 damper with 5 locations, and S2 includes 2 dampers with 10 different locations. Also, suspension configuration S3 has 3 dampers with 10 locations, S4 has 4 dampers with 5 different locations and S5 has 5 dampers. All these configurations are selected primarily to provide a sufficiently wide range for the investigation of the effect of the suspension settings on the tracked vehicle performance. Not all the configurations may have applications in practice.

Table 2. Half numbers and locations of dampers for various suspension configurations.

Suspension conf.	No. of dampers	Damper locations in the suspension				
S0	–	–	–	–	–	–
S1	1	wh1	wh2	wh3	wh4	wh5
S2	2	wh12	wh13	wh14	wh15	–
		wh23	wh24	wh25	–	–
		wh34	wh35	–	–	–
		wh4,5	–	–	–	–
S3	3	wh1,2,3	wh124	wh125	–	–
		wh1,3,4	wh135	–	–	–
		wh1,4,5	–	–		
		wh2,3,4	wh235		–	–
		wh2,4,5	–			
		wh3,4,5	–	–	–	–
S4	4	wh1,2,3,4	wh1235		–	–
		wh1,2,4,5	–	–	–	–
		wh1,3,4,5	–	–	–	–
		wh2,3,4,5	–	–	–	–
S5	5	All wheels				

3.2. *Characteristics of the terrain profiles*

Off-road vehicles are subjected to complex and severe excitations while driving over rough terrains; these excitations affect the hull vibration. The characteristics of these oscillations depend on: (i) the shape and dimensions of the road profile, (ii) the characteristics of the terrain (whether it is deformable or non-deformable) and (iii) the vehicle speed. To study off-road vehicle real excitations, it is important to identify the road profiles. The realistic road profiles that off-road vehicles traverse are non-periodic. It is not possible to find a road which includes all types of unevenness. There exist several models of road profiles that closely simulate realistic road excitations. Among the available terrains, the bump profiles are used in this study. It is also assumed that the bump terrains used in this study have rigid (non-deformable) characteristics. The simulations of the tracked vehicle model with the stated configurations are carried out over three bump road profiles referred to as shallow, medium and sharp roads and vehicle speeds of 10, 40 and 60 km/h. It should be noted that the speed of 60 km/h is achievable by a tracked vehicle on a smooth terrain but not on a rough terrain. It is used here as a limiting (maximum) speed value. On a rough or bumpy terrain, the maximum speed of a tracked vehicle is about 40 km/h. The bump road profiles are used for the evaluation of the transient response of most of the tracked vehicles as in [20]. The values of the parameters for the three bump road profiles are specified in Table 3 and the typical graph is shown in Figure 4. The vertical excitation of the first road wheel is characterised by the following equation:

$$z_{\mathrm{r}1}(t)=\begin{cases} h\{1-\cos\left[\omega_{\mathrm{r}}(t-0.5)\right]\}, & 0.5\le t\le 0.5+(w/V),\\ 0 & \text{otherwise,}\end{cases} \tag{4}$$

$$\omega_{\mathrm{r}}=2\pi f,\quad f=\frac{V}{w}, \tag{5}$$

where h represents the bump height of 0.1 m; w represents the bump width; ω_r represents the angular frequency and V represents the vehicle speeds. In addition, the vertical excitations to the other wheels z_{r2} to z_{r5} are described by

$$z_{\mathrm{r}i}(t)=z_{\mathrm{r}1}(t+\tau_i), \tag{6}$$

Table 3. Descriptions and parameters of bump terrains.

Road profile type	Height, h (m)	Width, w (m)
Shallow bump	0.1	5
Medium bump		2.5
Sharp bump		0.5

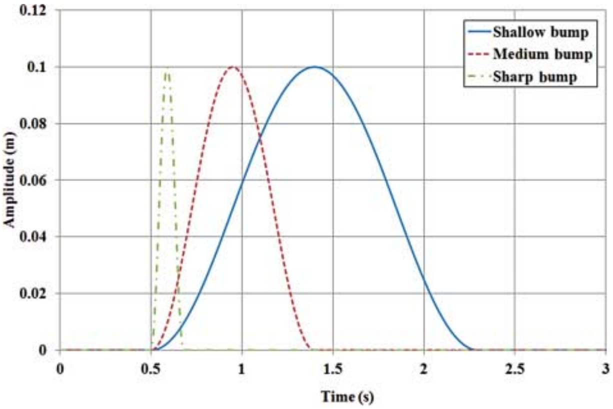

Figure 4. Typical bump road profiles.

where the time delay between the bump excitation of wheel 1 and the subsequent bump excitation of wheel i is given by

$$\tau_i = \frac{l_1 - l_i}{V}, \quad i = 2, \ldots, 5. \tag{7}$$

3.3. *Description of the objective function*

As stated in the introduction, there are several suspension indices that can be employed while evaluating the suspension performance. Among these indices, vibration dose value (VDV) and CF are utilised for that purpose.[8,21] The most critical values in a suspension design process are the maximum amplitude and settling time. The maximum amplitude is related to the CF, while the settling time is related to the VDV. Therefore, one of these two properties must be considered in the design.[8] In this research, assessment of the suspension performance was carried out by using a mixed objective function (MOF) that combines both the hull vertical bounce and PA. This combination uses the CF values of BA, BD, AA and PA to give an indication about the ride comfort improvement. The equation that describes the desired objective function can be expressed as follows:

$$\text{MOF} = \frac{1}{\sqrt{\sum_{i=1}^{4} \text{CF}_i^2}}, \quad \text{CF} = \frac{A_{i,\text{peak}}}{A_{i,\text{r.m.s}}}, \quad A_i = \text{BA, BD, AA, and PA}. \tag{8}$$

The bounce and pitch motions are the main criteria in the tracked vehicle suspension design that assess the ride comfort. It is required to minimise these criteria in order to improve the suspension performance.[11,14,22,23] The CF is used to evaluate the vehicle performance as in [9,24]. The suspension configurations with lower MOF are considered the best configurations that enhance the vehicle response.

3.4. *Simulation procedures*

A simulink model representing the half model of the passive suspension of the M113-A3 was developed in MATLAB/SIMULINK based on the derived equations of motion. The following analyses are performed for the three bump road profiles and at different vehicle speeds. For each bump road profile, the simulation is carried out for all the suspension configurations and the MOF is calculated. The lowest MOF values are used to select the best locations of the damper in the suspension. The time histories and the frequency domain of the bounce and pitch acceleration responses are then introduced to investigate the suspension performance of the selected configurations over various road profiles. It is worth mentioning that the value quoted for the damping coefficient is typical for tracked vehicle applications. Moreover, additional simulations are performed with soft and medium damping values (12,375 and 20,625 Ns/m) to study the effect of damping levels on the vehicle responses under shallow and sharp bumps.

4. Model validation using published data

The dynamic response of the undamped-tracked vehicle suspension is evaluated using the MATLAB program in order to calculate the associated natural frequencies. The predicted natural frequencies are obtained from the solution of the free undamped suspension system. Then, the predicted natural frequencies of the system are directly compared against a field measurement data of a real-tracked vehicle. The predictions are carried out for two sets of hull masses denoted as laden and unladen vehicle. Table 4 lists the predicted and measured natural frequencies of the system response and the corresponding modes of vibration. The measured frequencies are also for laden and unladen M113-tracked vehicles.[19] The results show good agreement between the predicted and measured frequencies. It should be noted that in reference,[19] the acceleration responses of the M113 have been measured when the vehicle negotiated different road profiles with different speeds. Then, the measured accelerations have been analysed to identify the natural frequencies which correspond to the maximum peak amplitudes.

Additional validation of the computer model is apparent through the undamped forced vibration analysis of the system responses for specific test conditions. The undamped model of the tracked vehicle was subjected to bump excitation of varying severity denoted as shallow, medium and sharp bump excitations, which are illustrated in Figure 4. The predicted results are presented in section 5.3. In these results, the fast Fourier transform (FFT) of the predicted time responses of the undamped suspension systems are shown by the dashed curves. The figures

Table 4. Predicted and measured undamped natural frequencies and associated modes.

	Undamped natural frequency (Hz)				
	Current work		Reference [19]		
Mode no.	(Laden)	(Unladen)	(Laden)	(Unladen)	Mode type
1	0.88	1.24	1.23	1.31	Hull pitch
2	1.48	1.75	1.65	1.85	Hull bounce
3	12.64	11.64	11.39	11.32	Wheel #1 bounce
4	12.64	12.64	12.2	11.08	Wheel #2 bounce
5	12.64	12.64	12.26	12.05	Wheel #3 bounce
6	12.65	12.66	12.34	12.01	Wheel #4 bounce
7	12.66	12.67	11.97	11.41	Wheel #5 bounce

Note: Laden vehicle with hull mass 5109 kg; unladen vehicle with hull mass 3660 kg.

show that the undamped natural frequencies of the undamped suspension are the same as those determined from the direct eigenfrequency analysis and shown in Table 4. The undamped frequencies are close to the measured natural frequencies as noted in Table 4. Thus, the validity of the theoretical model and of the MATLAB/Simulink simulation algorithm, which is based on the theoretical model, is established.

5. Discussion of predicted vehicle performance

The performances of the tracked vehicle with various numbers of dampers that are located at various wheel stations and for two levels of damping coefficients have been predicted. These predictions are for the tracked vehicle traversing shallow, medium and sharp bumps at speeds of 10, 40 and 60 km/h. It should be noted that in real applications, 10 km/h represents the low speed of military-tracked vehicles, while 40 and 60 km/h represent their maximum speeds on bumpy (or rough) and smooth terrains, respectively.

5.1. *Effect of varying damper locations on the vehicle performance*

In this part, the effect of varying the damper locations on the vehicle suspension performance is investigated. The suspension performance is evaluated under different road excitations and vehicle speeds. It is noted that in this analysis, the damping level is kept constant at a typical damping constant of M113-A3-tracked vehicle as listed in Table 1. The MOF values of all suspension configurations listed in Table 2 are calculated under shallow, medium and sharp bump terrains and the data are listed in Tables 5–8.

Table 5 shows the MOF of suspension configurations S1 under these excitations. The results denote that the damper locations have a significant effect on the vehicle performance. Also, the suspension configurations S1 have lower MOF values than the undamped suspension for the three bump road profiles.

Over the shallow bump and vehicle speed of 10 and 40 km/h, the suspension configuration S1 has two locations with the lowest MOF values which are at wheel 1 and wheel 5, respectively. In addition, when the vehicle traverses the same road with 60 km/h, the suspension fitted with a damper at wheel 1 or wheel 2 offers the lowest MOF values. Over the medium bump profile and vehicle speed of 10 km/h, the lowest MOF values occur when the suspension is equipped with dampers at wheel 1 and wheel 5. For the same road, when the vehicle speed is increased to 40 and 60 km/h, the suspension with dampers at wheel 1 or wheel 2 has the lowest MOF values. Over the sharp bump profile with speeds 10 and 40 km/h, the best locations are at

Table 5. MOF values of suspension configurations S1 under different bump excitations.

	Shallow			Medium			Sharp		
Suspension conf.	V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3
Undamped	0.196	0.33	0.297	0.243	0.314	0.197	0.261	0.294	0.113
wh1	0.142	0.106	0.096	0.138	0.081	0.065	0.085	0.063	0.036
wh2	0.166	0.122	0.106	0.166	0.094	0.074	0.127	0.13	0.103
wh3	0.198	0.129	0.127	0.163	0.127	0.1	0.124	0.143	0.040
wh4	0.171	0.118	0.116	0.172	0.119	0.101	0.102	0.132	0.123
wh5	0.154	0.111	0.110	0.158	0.116	0.096	0.088	0.089	0.054

Notes: $V_1 = 10$ km/h; $V_2 = 40$ km/h; $V_3 = 60$ km/h.

Table 6. MOF values of suspension configurations S2 under different bump excitations.

	Shallow			Medium			Sharp		
Suspension conf.	V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3
Undamped	0.196	0.33	0.297	0.243	0.314	0.197	0.261	0.294	0.113
wh12	0.147	0.111	0.087	0.154	0.085	0.066	0.089	0.092	0.06
wh13	0.145	0.107	0.090	0.151	0.077	0.066	0.082	0.091	0.076
wh14	0.148	0.099	0.091	0.128	0.085	0.069	0.082	0.090	0.079
wh15	0.155	0.091	0.086	0.129	0.087	0.073	0.088	0.096	0.046
wh23	0.170	0.116	0.095	0.169	0.092	0.072	0.100	0.113	0.082
wh24	0.151	0.108	0.094	0.164	0.090	0.073	0.097	0.096	0.072
wh25	0.148	0.100	0.093	0.14	0.096	0.076	0.086	0.109	0.094
wh34	0.171	0.111	0.106	0.151	0.108	0.087	0.095	0.118	0.094
wh35	0.156	0.104	0.104	0.135	0.108	0.085	0.085	0.100	0.091
wh45	0.156	0.106	0.105	0.151	0.109	0.084	0.089	0.111	0.086

Notes: $V_1 = 10\,\text{km/h}$; $V_2 = 40\,\text{km/h}$; $V_3 = 60\,\text{km/h}$.

Table 7. MOF values of suspension configurations S3 under different bump excitations.

	Shallow			Medium			Sharp		
Suspension conf.	V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3
Undamped	0.196	0.33	0.297	0.243	0.314	0.197	0.261	0.294	0.113
wh123	0.148	0.107	0.086	0.147	0.082	0.066	0.088	0.092	0.042
wh124	0.149	0.096	0.085	0.127	0.080	0.066	0.082	0.058	0.078
wh125	0.152	0.091	0.080	0.131	0.080	0.07	0.088	0.077	0.047
wh134	0.149	0.097	0.086	0.139	0.083	0.069	0.077	0.090	0.052
wh135	0.159	0.090	0.082	0.130	0.081	0.072	0.092	0.067	0.048
wh145	0.154	0.087	0.080	0.128	0.082	0.070	0.083	0.073	0.045
wh234	0.156	0.104	0.089	0.136	0.089	0.072	0.089	0.096	0.066
wh235	0.151	0.099	0.088	0.128	0.088	0.073	0.081	0.067	0.048
wh245	0.146	0.099	0.089	0.141	0.090	0.076	0.081	0.069	0.086
wh345	0.156	0.101	0.097	0.144	0.099	0.081	0.087	0.111	0.054

Notes: $V_1 = 10\,\text{km/h}$; $V_2 = 40\,\text{km/h}$; $V_3 = 60\,\text{km/h}$.

wheel 1 and wheel 5 while at speed 60 km/h, the best damper locations are at wheel 1 and wheel 3.

Table 6 shows the MOF values of the suspension configurations S2 under the same excitations. The results indicate the significant effect of the damper locations on the vehicle performance. Over the shallow bump and a speed of 10 km/h, the suspensions with dampers at wheels 13 and wheels 12 are the best configurations that have the lowest MOF values. From this point onwards, it should be noted that wheels xyz denote wheel location number x, y and z. Thus, wheels 13 and wheels 12 mean wheels 1, 3 and wheels 1, 2, respectively. When the vehicle traverses the same road with a speed of 40 km/h, the best suspension configurations are at wheels 14 and wheels 15. At 60 km/h, dampers at wheels 15 and wheels 12 have the lowest MOF values. Over the medium bump, the suspension with dampers at wheels 14 and wheels 15 has the lowest MOF values at 10 km/h, while dampers at wheels 13 and wheels 14 have the best locations at speed 40 km/h. At 60 km/h, dampers at wheels 12 and wheels 13 have the best locations that have the lowest MOF values. Over the sharp bump and at speeds of 10 and 40 km/h, dampers at wheels 14 and wheels 13 are the best locations, while dampers at wheels 15 and wheels 12 have the best damper locations at speed 60 km/h.

Likewise, the MOF of all suspension configurations S3 are shown in Table 7. Over the shallow bump, the damped suspension has a better performance than the suspension S0.

Table 8. MOF values of suspension configurations S4 and S5 under different bump excitations.

	Shallow			Medium			Sharp		
Suspension conf.	V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3
Undamped	0.196	0.33	0.297	0.243	0.314	0.197	0.261	0.294	0.113
wh1234	0.152	0.098	0.083	0.131	0.079	0.067	0.089	0.086	0.069
wh1235	0.157	0.091	0.079	0.133	0.077	0.067	0.089	0.072	0.060
wh1245	0.151	0.087	0.077	0.135	0.083	0.068	0.090	0.057	0.046
wh1345	0.157	0.088	0.078	0.129	0.077	0.069	0.088	0.075	0.059
wh2345	0.152	0.099	0.083	0.133	0.086	0.074	0.083	0.094	0.078
All wheels	0.157	0.089	0.076	0.140	0.078	0.068	0.096	0.049	0.039

Notes: $V_1 = 10\,\text{km/h}$; $V_2 = 40\,\text{km/h}$; $V_3 = 60\,\text{km/h}$.

At 10 km/h, the suspensions with dampers at wheels 245 and wheels 123 have the lowest MOF, while at 40 km/h, the suspensions with dampers at wheels 145 and wheels 135 have the best locations that offer better performance. For the medium bump and at 10 km/h, the best locations for the dampers are at wheels 124 and wheels 235, while at a medium speed of 40 km/h, the best locations are at wheels 124 and wheels 125. At 60 km/h, the best damper locations are at wheels 124 and wheels 123. For the sharp bump at 10 km/h, wheels 134 and wheels 235 have the best damper locations, while the best locations at 40 km/h are at wheels 124 and wheels 135. At 60 km/h, the best damper locations are at wheels 123 and wheels 145.

Table 8 lists the MOF values of the suspension configurations S4 and S5. Also, all the damped suspension configurations have lower MOF values than the undamped suspension S0. Over the shallow bump and at 10 km/h, the suspension S4 has two locations with the lowest MOF which are at wheels 1245 and wheels 2345 while dampers at wheels 1245 and wheels 1345 have the best locations at a speed of 40 km/h. At a high speed, dampers at wheels 1245 and 1345 have the lowest MOF values. Over the medium bump, wheels 1345 and wheels 1234 are the best damper locations at 10 km/h, while wheels 1235 and wheels 1345 are the best damper locations at 40 km/h. At speed of 60 km/h, wheels 1234 and wheels 1235 are the best damper locations.

It can be seen from the results that the damper locations affect the vehicle performance and the best damper locations over specific road profile are changed when the vehicle speed is varied. In order to select the best damper locations that suit different bump road profiles, the MOF values for all speeds are summed together. Then, the summed MOF values for each road are added together to give a resultant MOF per each suspension configuration. After that, the suspension with the lowest resultant MOF value is considered the best damper location that offers good suspension performance as seen from Table 9. The results show that the damper locations have a significant effect on the vehicle performance. The resultant MOF gives an indication of the best locations. From the results, it can be seen that there are five suspension configurations with the lowest MOF values which are S1-1, S2-15, S3-125, S4-1245 and S5-all. It is noted that suspensions with dampers at wheels 125 are chosen instead of damper locations at wheels 145 as the former is a standard suspension settings of a typical off-road vehicles.

5.2. *Effect of varying damping levels of the dampers on the vehicle performance*

In this part, the effect of the damping levels of the hydraulic dampers on the vehicle performance is investigated under shallow and sharp bump profiles. Two damping levels namely, low ($D_1 = 12,375\,\text{Ns/m}$) and medium ($D_2 = 20,625\,\text{Ns/m}$) damping are chosen for this analysis. In addition to the damping values, the vehicle traverses the road profiles with low

Table 9. MOF for various suspension configurations under different bump excitations.

		Sum of MOF for all speeds			
Suspension conf.	Damper locations	Shallow	Medium	Sharp	Sum of MOF for all roads
S0	Undamped	0.669	0.755	0.824	2.248
S1	At wh1	0.186	0.286	0.345	0.817
	At wh5	0.232	0.371	0.377	0.980
S2	At wh14	0.253	0.283	0.339	0.875
	At wh15	0.231	0.290	0.333	0.855
S3	At wh125	0.213	0.282	0.325	0.820
	At wh145	0.202	0.281	0.322	0.806
S4	At wh1245	0.194	0.288	0.316	0.799
	At wh1345	0.223	0.277	0.324	0.824
S5	At all wheels	0.186	0.287	0.324	0.797

Table 10. MOF values of suspension configurations with various damping levels.

	Shallow bump				Sharp bump			
Suspension conf.	$V_1; D_1$	$V_1; D_2$	$V_2; D_1$	$V_2; D_2$	$V_1; D_1$	$V_1; D_2$	$V_2; D_1$	$V_2; D_2$
S0	0.221	0.221	0.316	0.316	0.164	0.164	0.247	0.247
S1-1	0.212	0.206	0.155	0.142	0.114	0.108	0.067	0.061
S2-15	0.217	0.221	0.138	0.122	0.127	0.120	0.097	0.086
S3-125	0.218	0.218	0.132	0.114	0.133	0.121	0.080	0.074
S4-1245	0.217	0.215	0.128	0.111	0.131	0.127	0.064	0.060
S5-all	0.224	0.222	0.125	0.110	0.138	0.135	0.060	0.057

Notes: $D_1 = 12375\,\mathrm{Ns/m}$; $D_2 = 20625\,\mathrm{Ns/m}$; $V_1 = 10\,\mathrm{km/h}$; $V_2 = 60\,\mathrm{km/h}$.

($V_1 = 10\,\mathrm{km/h}$) and high speeds ($V_2 = 60\,\mathrm{km/h}$). The MOF values for suspension configurations S0, S1-1, S2-15, S3-125, S4-1245 and S5-all were calculated at the proposed excitations and speeds where the wheel numbers are appended after the configurations.

The calculated MOF values are shown in Table 10, while Figures 5 and 6 show the improvement in the MOF values of the best five suspension configurations with respect to the undamped suspension under shallow and sharp bump roads. Figure 5 shows that the effect of variation in the damping level on the performance is relatively small under low speed. However, at high speed the damping effect on the suspension performance is clearly observed. The increase in the damping level improves the damped suspension responses with respect to the undamped suspension.

Alternatively, Figure 6 shows the MOF results under the same damping levels but over the sharp bump profile. It is shown that at low speed, although the vehicle response is improved by increasing the damping level, the suspension performance is reduced when the number of dampers is increased. However, at high speed, the suspension response is improved when the number of dampers is increased. This means that the rough roads introduce high vibration levels into the suspension and high damping levels are required for vibration attenuation.

5.3. *Effect of varying number of dampers on the vehicle performance*

This section presents the effect of the number of dampers in the suspension on the vehicle performance. The time histories and frequency spectra of the BA and AA responses of the best suspension locations that have been selected in Section 5.1 are presented and compared with the undamped response under the same excitations and speeds.

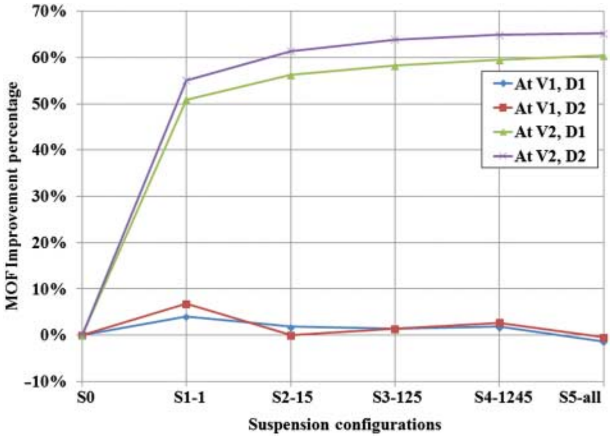

Figure 5. Improvement in MOF values of suspension configurations under shallow bump profiles at different damping levels and speeds ($D_1 = 12,375\,\mathrm{Ns/m}$; $D_2 = 20,526\,\mathrm{Ns/m}$; $V_1 = 10\,\mathrm{km/h}$; $V_2 = 60\,\mathrm{km/h}$).

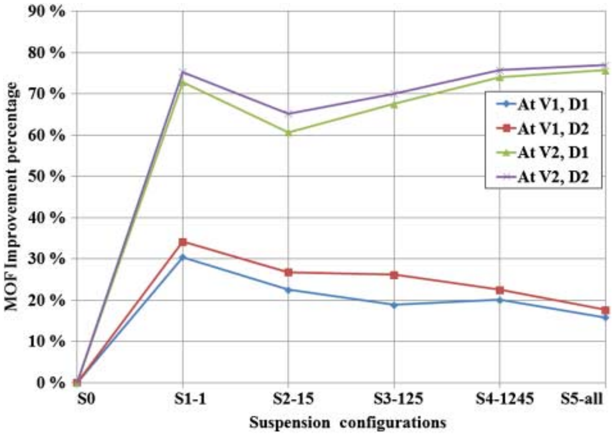

Figure 6. Improvement in MOF values of suspension configurations under sharp bump profiles at different damping levels and speeds ($D_1 = 12,375\,\mathrm{Ns/m}$; $D_2 = 20,526\,\mathrm{Ns/m}$; $V_1 = 10\,\mathrm{km/h}$; $V_2 = 60\,\mathrm{km/h}$).

5.3.1. *Shallow bump responses*

The system responses of the suspension system with the best configurations under the shallow bump excitation are shown in Figure 7(a) and 7(b). The time and frequency domain responses of BA and AA responses of all suspension configurations are compared with those for the undamped suspension at different speeds of 10, 40 and 60 km/h. The results from Figure 7(a) show that the damped suspension dissipates the energy caused by the shallow bump excitation, reduce the settling time and improves the suspension performance at all speeds. The peak-to-peak (PTP) values and improvement percentage (which is the difference between undamped and damped values over the undamped value) of the BA of all suspension configurations are listed in Table 11. The data indicate that the amount of the damping force and the vehicle speed have a significant effect on the suspension performance. For instance, at 10 km/h the suspension configurations S4-1245 and S5-all have the highest reduction in the PTP values, followed by S3-125, S2-15 and S1-1.

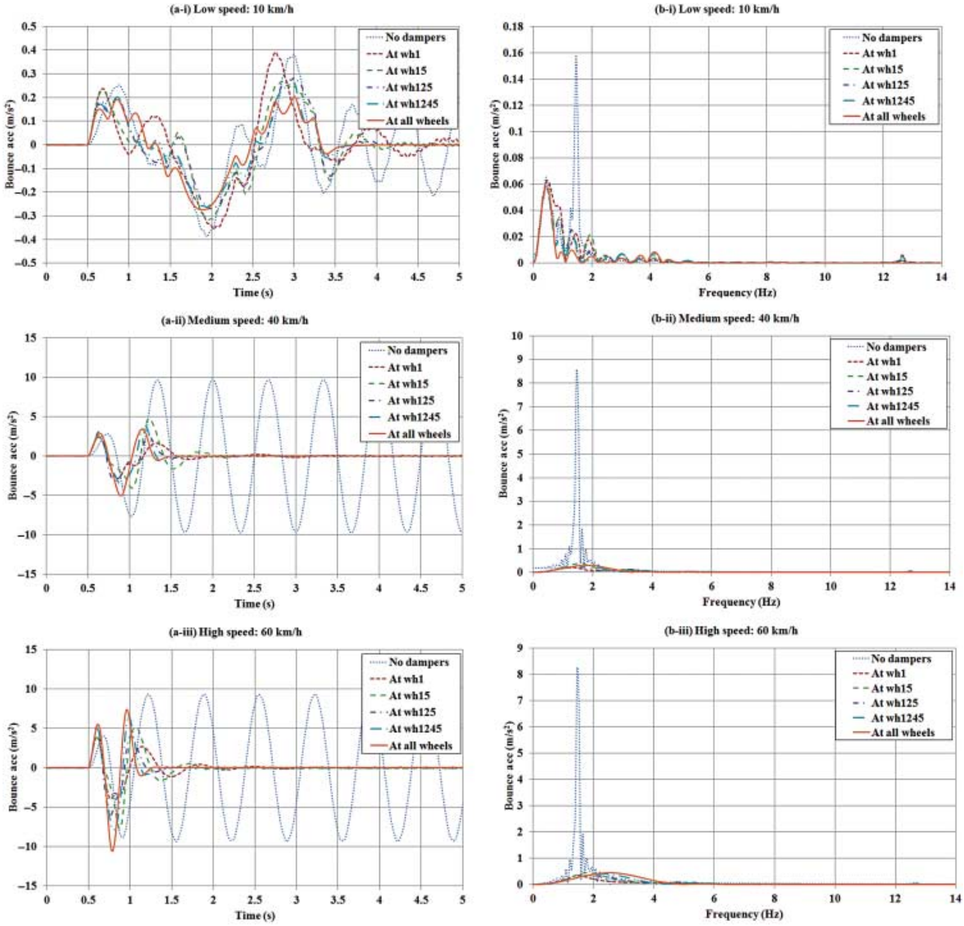

Figure 7. Influence of varying number of dampers on BA responses under shallow bump excitation with 5 m width and 0.1 m height.

When the vehicle negotiates the same road at 40 and 60 km/h, the road-induced vibration transmitted to the vehicle body is increased. Therefore, the suspension should isolate the vehicle body from these vibrations. One can say that increasing the number of dampers in the suspension suppresses the road vibration. But, the results from the table confirm that at 40 and 60 km/h, increasing the damping degrades the PTP responses and increasing the number of dampers over 3 reduces the vehicle performance. Figure 7(b) shows the absolute values of the FFT responses of the BA responses under the same excitations. The damped suspensions have significantly reduced the BA resonant peak at 1.5 Hz under all speeds. The r.m.s. values of the BA responses are listed in Table 11. The results from the table show that the configurations S4-1245 and S5-all have the lowest r.m.s. values under the shallow bump at 10 km/h. However, over the medium and sharp bump, the suspension configurations S1-1 and S3-125 are superior in enhancing the vehicle performance.

Similarly, Figure 8(a) and 8(b) illustrates the time and frequency domain of the AA responses under the same excitations. The results shown in Figure 8(a) demonstrate that the damped suspension configurations have a better performance than the undamped suspension S0 for all speeds. Table 12 shows the PTP values of the AA responses under the same excitations

Table 11. PTP and r.m.s. values of BA under shallow bump excitation.

	PTP (ms^{-2})						r.m.s. (ms^{-2})					
Description	$V = 10$	ΔPTP%	$V = 40$	ΔPTP%	$V = 60$	ΔPTP%	$V = 10$	Δrms%	$V = 40$	Δrms%	$V = 60$	Δrms%
S0	0.78	0.0	19.69	0.0	18.88	0.0	0.15	0.0	6.55	0.0	6.35	0.0
S1-1	0.76	2.6	5.32	73.0	7.95	57.9	0.11	26.7	0.49	92.5	0.74	88.3
S2-15	0.59	24.4	9.00	54.3	12.98	31.2	0.09	40.0	0.82	87.5	1.08	83.0
S3-125	0.56	28.2	6.31	68.0	11.42	39.5	0.09	40.0	0.58	91.1	0.92	85.5
S4-1245	0.53	32.1	7.84	60.2	14.59	22.7	0.08	46.7	0.69	89.5	1.16	81.7
S5-all	0.49	37.7	8.49	56.9	18.14	3.9	0.08	46.7	0.75	88.5	1.34	78.9

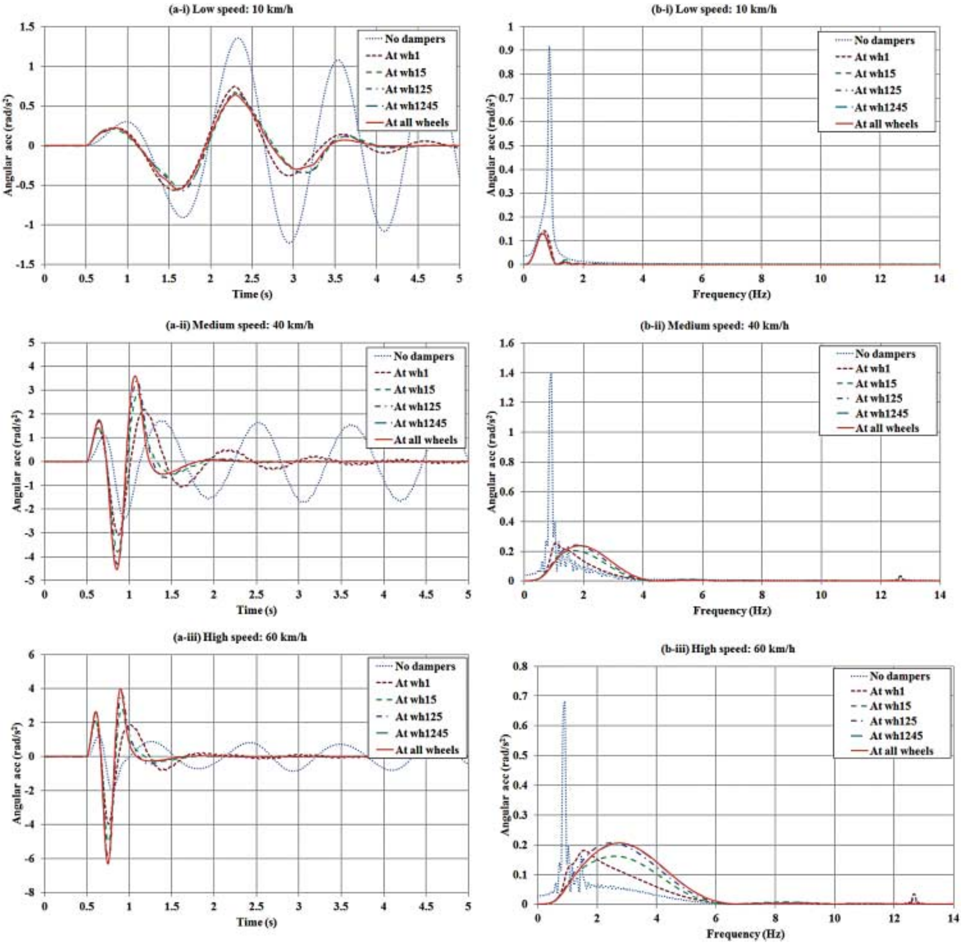

Figure 8. Influence of varying number of dampers on AA responses under shallow bump excitation with 5 m width and 0.1 m height.

and speeds. The table indicates that the damped suspensions have better responses than the undamped suspension. The suspension configurations S5-all and S4-1245 have the biggest reductions in the PTP values, followed by the configurations S3-125, S2-15 and S1-1. However, the PTP values of the AA responses at 40 and 60 km/h are increased when the number of dampers is increased. This confirms that increasing the damping force is not always beneficial for vibration isolation.

Table 12. PTP and r.m.s. values of AA under shallow bump excitation.

	PTP (rads^{-2})						r.m.s. (rads^{-2})					
Description	$V = 10$	ΔPTP%	$V = 40$	ΔPTP%	$V = 60$	ΔPTP%	$V = 10$	Δrms%	$V = 40$	Δrms%	$V = 60$	Δrms%
S0	2.61	0.0	4.14	0.0	3.28	0.0	0.74	0.0	1.15	0.0	0.60	0.0
S1-1	1.32	49.4	5.33	−28.7[a]	6.10	−85.8	0.19	74.3	0.53	53.9	0.51	14.5
S2-15	1.22	53.3	6.75	−63.0	7.91	−141.0	0.18	75.7	0.56	51.3	0.56	5.5
S3-125	1.27	51.3	7.8	−88.4	9.89	−201.2	0.19	74.3	0.65	43.5	0.70	−17.1
S4-1245	1.2	54.0	8.19	−97.8	10.31	−214.1	0.18	75.7	0.66	42.6	0.71	−18.9
S5-all	1.2	54.0	8.21	−98.3	10.37	−215.8	0.18	75.7	0.66	42.6	0.71	−19.3

[a] Negative signs correspond to an increase in the response.

In Figure 8(b), the damped suspensions have reduced the AA resonant peaks at 0.9 Hz at all speeds. All the suspension configurations have reduced the r.m.s. values of the AA responses. However, suspension configurations S1-1 and S2-15 have the highest reduction in r.m.s. values of AA at 40 and 60 km/h. It is to be noted that over the shallow bump road, the number of dampers has a significant effect on the suspension performance. For example, at low speed,

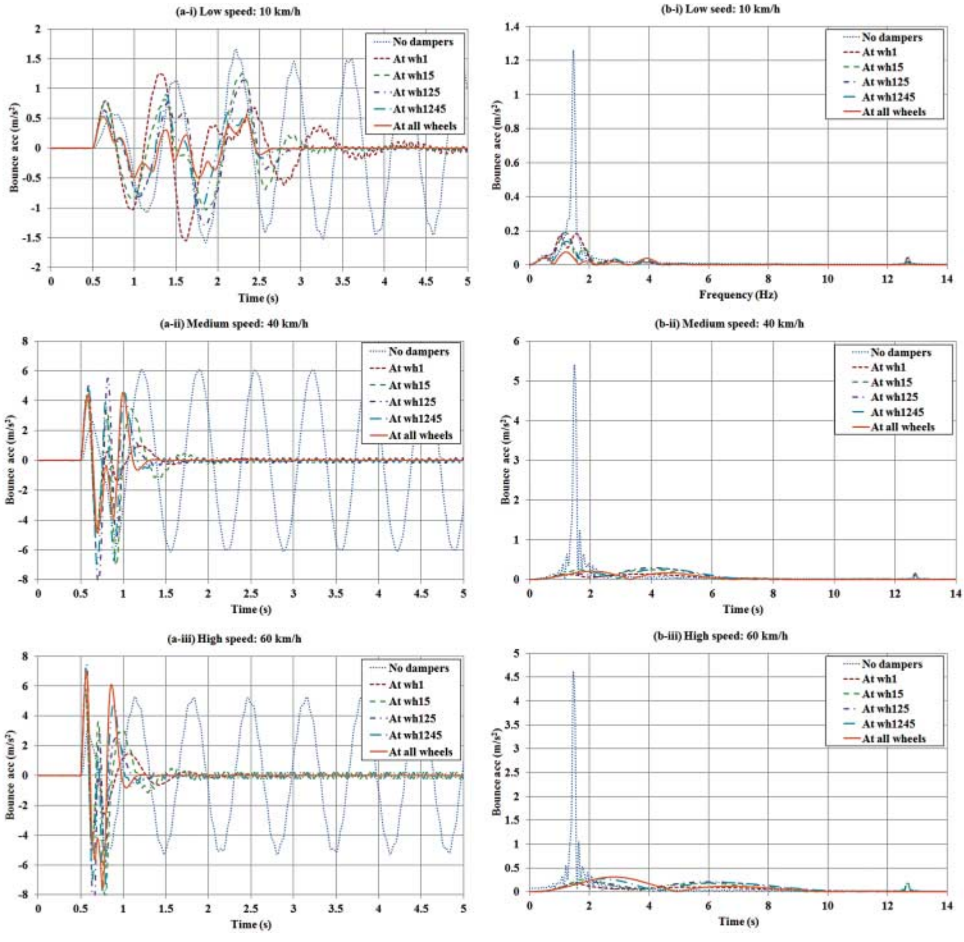

Figure 9. Influence of varying number of dampers on BA responses under medium bump excitation with 2.5 m width and 0.1 m height.

Table 13. PTP and r.m.s. values of BA under medium bump excitation.

	PTP (ms^{-2})						r.m.s. (ms^{-2})					
Description	$V = 10$	ΔPTP%	$V = 40$	ΔPTP%	$V = 60$	ΔPTP%	$V = 10$	Δr.m.s.%	$V = 40$	Δrms%	$V = 60$	Δrms%
S0	3.28	0.0	12.40	0.0	10.73	0.0	0.97	0.0	4.14	0.0	3.54	0.0
S1-1	2.82	13.8	9.16	26.1	10.65	0.8	0.35	63.8	0.55	86.8	0.59	83.3
S2-15	2.31	29.5	11.37	8.3	14.55	−35.5	0.31	68.3	0.91	77.9	0.93	73.8
S3-125	2.47	24.6	13.86	−11.8	16.85	−57.0	0.31	68.4	0.99	76.1	0.96	72.8
S4-1245	1.98	39.4	11.98	3.4	16.42	−53.0	0.23	76.1	0.97	76.6	1.05	70.4
S5-all	1.05	68.0	9.53	23.1	14.72	−37.1	0.14	85.9	0.74	82.2	1.04	70.7

when the number of dampers is increased, the BA response is improved. However, at medium and high speeds, the BA response becomes worse as the number of dampers is increased. Also, at medium and high speeds, the suspensions S1-1, S2-15 and S3-125 offer the optimal settings that provide the best reduction in the BA peaks over shallow bump. However, the AA responses are increased when the number of dampers is increased.

5.3.2. *Medium bump responses*

Over the medium bump road, the excitation frequency, which is defined as the ratio of the vehicle speed over the bump width, is increased compared with the shallow bump road. The increase in the road frequency introduces high vibration levels to the suspension system. Figure 9(a) and 9(b) shows the system responses of the BA of all suspension configurations. From Figure 9(a), the results indicate that all the damped suspension configurations have better acceleration responses than the undamped suspension. The PTP values of the BA for all suspension configurations at various speeds are summarised in Table 13. At 10 km/h, all the damped suspension configurations have better reduction in the PTP values of BA than the undamped suspension. Also, the per cent reduction is increased when the suspension have more than three dampers. This appears from the table as the suspension configurations S5-all and S4-1245 have the highest reduction in the PTP values.

It is noticed that when the speed is increased to 40 km/h, the suspension configurations S1-1 and S5-all have the lowest BA peaks. At 60 km/h, all the suspension configurations have a poorer performance than S0. All the suspension configurations except the suspension configuration S1-1 increase the PTP values of the BA. Figure 9(b) shows the frequency domain responses of all suspension configurations under the same excitations. It can be seen that the damped suspension reduces the BA resonant peaks at the resonant frequency of 1.5 Hz, while the suspension S0 has a better performance than the damped suspension over the frequency range from 2 to 6 Hz. The r.m.s. values of the BA responses are listed in Table 13. The table shows that the number of the dampers affects the BA r.m.s. and the suspension configurations S1-1, S2-15 and S3-125 have the biggest reductions in the r.m.s. values at speeds of 40 and 60 km/h.

Similarly, the AA responses under the medium excitation are shown in Figure 10(a) and 10(b). It is seen that all the damped suspension configurations have a significant effect on the suspension performance. The damped suspension improves the AA responses at all speeds. The PTP values of the AA are listed in Table 14. At 10 km/h, the damped suspension performance has improved. In addition, the suspension configurations S4-1245 and S5-all offer the highest reduction in the PTP values of AA. This is followed by the suspension configurations S1-1 and S2-15. For speeds 40 and 60 km/h, the undamped suspension has the lowest peak values. Figure 10(b) illustrates the frequency domain of the AA responses under the same excitation. Although the damped suspension has reduced the AA peak at the resonant

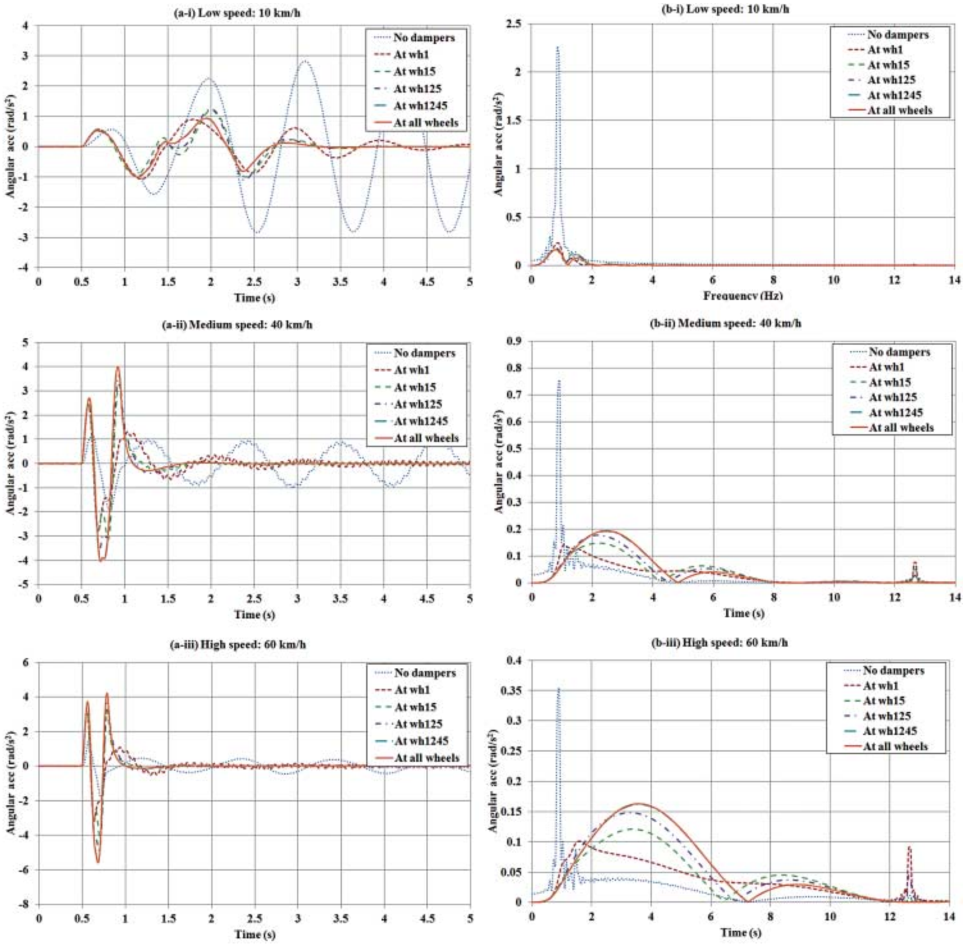

Figure 10. Influence of varying number of dampers on AA responses under medium bump excitation with 2.5 m width and 0.1 m height.

Table 14. PTP and r.m.s. values of AA under medium bump excitation.

	PTP (rads^{-2})						r.m.s. (rads^{-2})					
Description	$V = 10$	ΔPTP%	$V = 40$	ΔPTP%	$V = 60$	ΔPTP%	$V = 10$	Δr.m.s.%	$V = 40$	Δrms%	$V = 60$	Δrms%
S0	5.76	0.0	3.16	0.0	3.26	0.0	1.85	0.0	0.65	0.0	0.33	0.0
S1-1	1.99	65.4	5.26	−66.8	6.47	−98.3	0.32	82.9	0.40	37.5	0.39	−18.1
S2-15	2.24	61.1	6.46	−104.5	7.49	−129.6	0.30	83.9	0.50	22.6	0.49	−46.8
S3-125	2.36	59.1	7.32	−132.1	8.60	−163.4	0.30	83.6	0.57	11.7	0.59	−78.8
S4-1245	1.96	66.0	8.11	−157.0	9.82	−200.8	0.26	85.9	0.62	3.9	0.64	−92.1
S5-all	1.95	66.1	8.13	−157.5	9.88	−202.7	0.26	85.9	0.62	3.5	0.64	−92.9

frequency (0.9 Hz) at all speeds, the undamped suspension has a better performance in the frequency range from 2 to 8 Hz. Table 14 summarises the r.m.s. values of the AA responses. It is seen that increasing the number of dampers at 10 and 40 km/h offers a significant effect on the suspension performance. However, at 60 km/h, the dampers have a negative effect on the vehicle performance as the response is deteriorated when the number of dampers is increased.

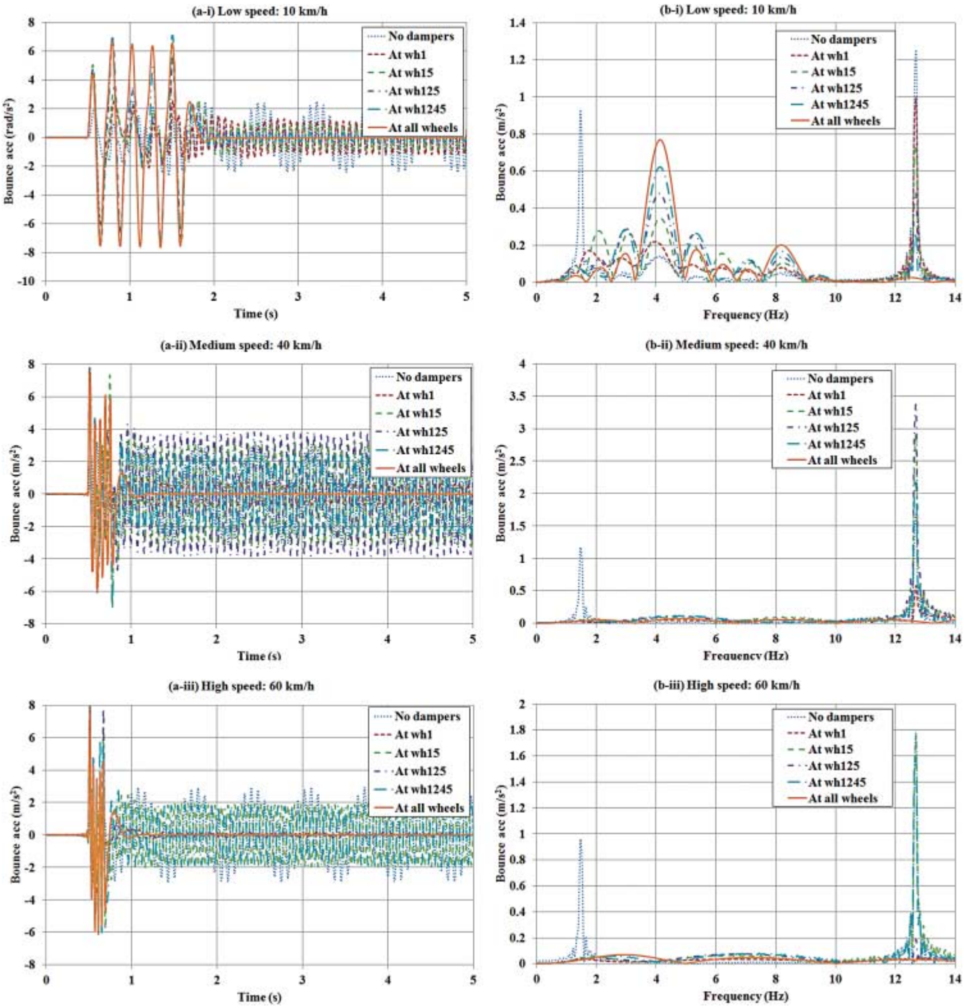

Figure 11. Influence of varying number of dampers on BA responses under sharp bump excitation with 0.5 m width and 0.1 m height.

5.3.3. *Sharp bump responses*

In this section, the suspension performance is investigated under severe excitation which is the sharp road profile with 0.5 m width (too short for full-size tracked vehicles). The bounce and pitch acceleration of the undamped and damped suspension configurations are shown in Figures 11 and 12. The BA responses shown in Figure 11(a) indicate that under the sharp terrains the suspension performance is highly influenced by the number of dampers fitted to the suspension. The suspension responses are significantly increased when the suspension is fitted with any dampers. Table 15 lists the PTP values of the BA responses of the suspension configurations under sharp bump excitation. It can be seen that the BA responses are significantly increased when the suspension is equipped with any number of dampers. The configurations S1-1 and S2-15 offer the lowest PTP values at all speeds. This shows that the increase in the damping forces is not always favourable to vibration attenuation especially over rough bump roads. Figure 11(b) shows that at 10 km/h, the damped suspension reduces the BA resonant peaks while the response is increased after the resonant frequency. In fact, the

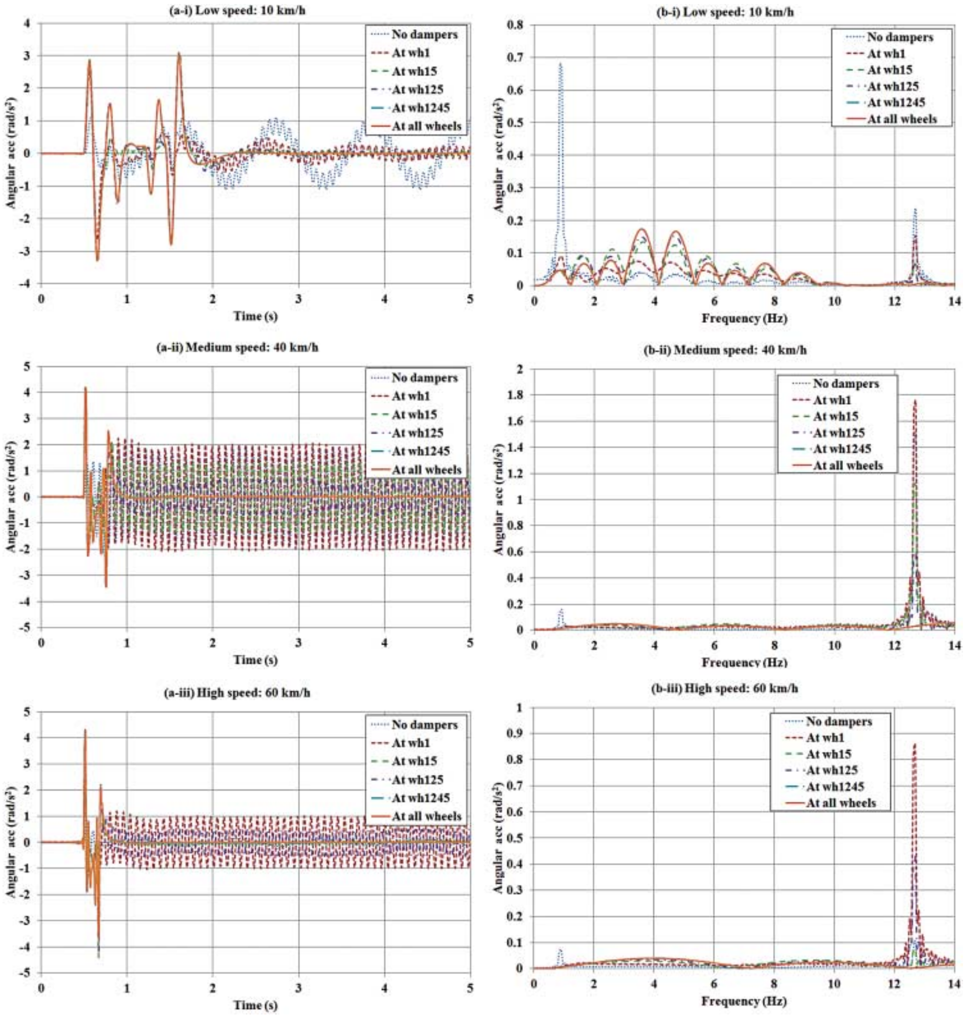

Figure 12. Influence of varying number of dampers on AA responses under sharp bump excitation with 0.5 m width and 0.1 m height.

stiffness of the damped suspension has increased such that the bounce frequency of the hull has been shifted from 1.5 Hz (for the undamped case) to about 4.2 Hz (for the damped cases) This is clearly shown in Figure 11(b). However, it should be noted that the FFT analysis of the original time data has produced sidebands of the main spectral amplitude response at the new resonant frequency. Nevertheless, the figure shows that the wheel bounce frequency remains approximately the same for both the damped and undamped cases.

When the vehicle traverses over the same sharp bump road at the medium speed of 40 km/h, the S1-1 and S5-all suspension configurations have reduced the BA peaks while configurations S2-15, S3-125 and S4-1245 increase the BA peaks as shown in Table 15 and Figure 11(a). However, it is clear from Figure 11(b) that this increase in the BA peaks is due to the wheel bounce of frequency 12.6 Hz. The hull bounce, which occurs around 4.5 Hz, is considerably suppressed in amplitude due to the damped suspension compared with the undamped suspension case. Similarly, when the vehicle traverses the sharp bump at the high speed of 60 km/h, the S1-1 and S3-125 configurations have the highest reduction in the BA peaks. In addition,

Table 15. PTP and r.m.s. values of BA under sharp bump excitation.

	PTP (ms^{-2})						r.m.s. (ms^{-2})					
Description	$V = 10$	ΔPTP%	$V = 40$	ΔPTP%	$V = 60$	ΔPTP%	$V = 10$	Δrms%	$V = 40$	Δrms%	$V = 60$	Δrms%
S0	5.19	0.0	6.48	0.0	6.10	0.0	1.23	0.0	1.58	0.0	1.53	0.0
S1-1	10.69	−105.8	13.34	−105.8	12.03	−97.2	1.03	16.4	0.65	58.9	0.35	77.0
S2-15	13.21	−154.4	15.76	−143.0	14.14	−131.8	1.15	6.4	2.31	−46.3	1.42	6.6
S3-125	14.60	−181.2	14.54	−124.2	13.54	−122.1	1.24	−1.1	2.73	−72.8	0.57	62.9
S4-1245	14.76	−184.2	15.46	−138.4	13.74	−125.3	1.39	−13.2	1.88	−18.8	1.44	5.7
S5-all	14.39	−177.0	14.30	−120.6	13.68	−124.3	1.59	−29.5	0.77	51.4	0.59	61.5

Table 16. PTP and r.m.s. values of AA under sharp bump excitation.

	PTP (rads^{-2})						r.m.s. (rads^{-2})					
Description	$V = 10$	ΔPTP%	$V = 40$	ΔPTP%	$V = 60$	ΔPTP%	$V = 10$	Δrms%	$V = 40$	Δrms%	$V = 60$	Δrms%
S0	2.29	0.0	4.16	0.0	2.09	0.0	0.60	0.0	1.22	0.0	0.12	0.0
S1-1	5.20	−126.8	7.02	−69.0	6.36	−203.8	0.31	48.4	1.45	−19.0	0.72	−495.5
S2-15	6.38	−178.6	8.18	−96.7	9.54	−355.5	0.44	26.6	0.97	20.6	0.27	−120.2
S3-125	6.53	−184.7	8.62	−107.3	9.26	−342.3	0.47	22.3	0.58	52.0	0.45	−269.0
S4-1245	6.43	−180.5	8.78	−111.1	8.81	−320.5	0.48	20.0	0.34	72.3	0.27	−125.1
S5-all	6.42	−180.3	8.76	−110.8	8.81	−320.9	0.48	20.1	0.34	72.3	0.27	−125.3

Figure 11 shows that the peak values of the BA responses in both the time and frequency domains are less than the corresponding BA responses at the medium speed of 40 km/h.

The time history of the AA of all suspension configurations under the same sharp bump road excitation is illustrated in Figure 12(a). The response of the damped suspension configurations has a lower settling time than the undamped suspension. However, the undamped suspension PTP responses are lower than the damped suspension configurations. The suspension configurations S1-1 and S2-15 have the lowest increase in the PTP values of the AA amplitudes as can be seen from Table 16. The frequency domain responses shown in Figure 12(b) indicate that the resonant AA peaks are reduced at all speeds. However, the damped suspension responses have significant amplitudes at the wheel resonant frequency (12.7 Hz). The results listed in Table 16 show the r.m.s. values of the AA under different speeds. The data show that all the damped suspension configurations have reduced the r.m.s. values of the AA responses at 10 and 40 km/h speeds. However, the damped suspension is unable to suppress the vibration from the road at the wheel bounce frequencies.

Over the sharp bump road, the damped suspension system is able to effectively isolate vehicle vibration at hull bounce and pitch resonant frequencies, but fails to effectively suppress the vibration at wheel bounce frequencies. For shallow bump roads, the required damping force necessary to damp the vibration is small. But when the vehicle traverses a rough road or increases its speed, the dampers should have a sufficient damping force to suppress the road vibration. It can be seen that increasing the number of dampers in the suspension offers a better suspension performance at low speed under shallow roads. However, the suspension with the same configurations is less effective in suppressing the road vibration for medium and sharp bump roads.

6. Conclusions

The paper has presented a detailed analysis of the effect of different suspension configurations on the tracked vehicle performance under various bump terrains. A two-dimensional model of a tracked vehicle suspension system is exploited to investigate the vehicle performance under different bump terrains. The validity of the model was established by comparing the predicted undamped frequencies of the tracked vehicle with published experimentally measured undamped frequencies. The agreement between the predicted and measured frequencies has been shown to be close.

From the analysis, the best suspension configurations are indentified using the MOF that combine the CF of BA, BD, AA, and PA for suspension evaluation. It is obvious from the calculated MOF that the optimal suspension performance has lower peak amplitudes which result in lower CF. In an optimum design of suspension, ride comfort characteristics must be included in the objective function. Therefore, the proposed MOF indicates the best suspension configurations for minimal hull bounce and pitch. The MOF values of the damped suspension system are compared with those of the undamped suspension under different excitations and speeds.

Among the design parameters, the damper locations have been shown to be of importance. The suspension performance is improved when the dampers are fitted to the extreme wheels rather than the intermediate wheels. The locations of the dampers at these wheels preserve the best suspension performance at high speeds over different bump terrains. The proposed objective function shows that the suspension with 2 dampers fitted at wheels 15 or 3 dampers fitted at wheels 125 are the best suspension configurations for vibration attenuation under different bump road conditions.

Also, the effect of varying the damping levels on the vehicle performance was investigated. The suspension configurations with low and medium damping coefficient were tested under shallow and sharp bump roads. The results show that for the same suspension configuration, increasing the damping coefficient is required for road vibration attenuation at high speed over sharp bump roads.

Furthermore, the results confirm that increasing the number of dampers in the suspension is not always beneficial for vibration attenuation. Over the shallow and medium bump terrains and at 10 and 40 km/h, the BA responses are reduced when the number of dampers is increased. On the other hand, the AA responses are increased when the numbers of dampers are increased for the same excitations. The results also indicate that the sharp bump terrains introduce severe vibration levels that degrade the suspension performance even at low speed. It can be seen that the optimum suspension performance is maintained by minimising both the BA and AA accelerations. Therefore, optimisation of the best suspension configurations should improve its dynamic performance over various terrains. Overall, the results show that suspension configurations S2-15 and S3-125 are the optimal configurations under all bump terrains.

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