Original Research Article: full paper

(2024), «EUREKA: Physics and Engineering»
Number 5

STUDY ON TERRAIN RESPONSE OF THE MILITARY MOBILE REPAIR VEHICLE TOWING POWER GENERATOR TRAILER BEFORE AND AFTER IMPROVEMENT

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Abstract

Mobile repair vehicles play an indispensable role on the battlefield and are increasingly being improved to enhance their effectiveness. When moving to repair locations on the battlefield, they often tow trailers, which include power generator sets. In some cases, these generator sets are replaced by trailers to transport ammunition or carry wounded soldiers. The article proposes improvements to the suspension system on the generator trailers and discusses the impact of vehicle speed and random road roughness on the movement of the mobile repair vehicle-trailer combination before and after the improvements. A dynamic model of the multi-body system is constructed, with the towing vehicle being a three-axle truck. The random roughness profile of the road surface is determined from simulation results based on ISO 8068 standards. The equations of motion are established using Lagrange's method and solved through simulation using Matlab software. The results of the article indicate the oscillation of the mobile repair vehicle-trailer combination when traveling at speeds of 36 km/h and 54 km/h on road surfaces with random roughness levels of class D and class E. After the improvement of the suspension system on the generator trailers, smoother trailer motion is observed. The study has shown that the vertical oscillation amplitude of the trailer decreased by up to 18 %, while the oscillation speed decreased by as much as 40 %. The findings provide a basis for further improving the suspension system on generator trailers to minimize oscillations, which is crucial for replacing generator trailers with specialized trailers for transporting ammunition or wounded soldiers on the battlefield. This is a significant issue in the field of national security and defense.

Keywords: military vehicles, random road roughness, three-axle truck, dynamics, multi-body system.

DOI: 10.21303/2461-4262.2024.003384

1. Introduction

The military forces of various nations are equipped with specialized equipment and machinery for engineering tasks such as road clearance, mobile repair, and battlefield rescue operations. Technological advancements in manufacturing have led to the emergence of modern, feature-rich equipment, but the cost of military products with advanced production technology remains high. Therefore, many countries still use equipment and machinery that have been manufactured for a long time while continuously seeking improvements to enhance their effectiveness. Some countries, like Vietnam, Belarus, Republic of Kazakhstan, Kyrgyzstan, Armenia, and Tajikistan, still utilize equipment produced by the former Soviet Union. The MTO-AT military mobile repair vehicle (**Fig. 1**), manufactured by the Soviet Union, is based on the chassis of the Zil 131 truck and is specifically designed for towing and repairing damaged vehicles to assembly points or conducting on-site repairs. In certain situations, it is also used for transporting ammunition, logistical materials, or wounded personnel. The MTO-AT mobile repair vehicle is equipped with various tools and equipment such as lathes, grinders, and drills, all of which require power to operate. Therefore, these mobile repair vehicles are integrated with an additional power generator set mounted on a trailer towed behind them.

Fig. 1. MTO-AT mobile repair vehicle towing a power generator trailer

The power generator set mounted on the trailer does not have a suspension system; the two wheels of the trailer are connected by a long axle. During the movement of the MTO-AT mobile repair vehicle to the location of the damaged vehicles, it always tows this trailer. Comparing this with the movement process of a truck towing a trailer, it is possible to observe the following characteristic features of the mobile repair vehicle-trailer combination:

1) due to their involvement in battlefield rescue operations, mobile repair vehicle-trailer combinations often traverse challenging terrains such as hilly or mountainous areas, as well as uneven road surfaces with random roughness;

2) the structural characteristic of the power generator trailer's movement system lacks suspension. Therefore, when moving alongside the towing vehicle, the power generator trailer experiences significant oscillations in response to stimuli from the road surface.

These studies share many similarities in researching the movement process of mobile repair vehicles towing power generator trailers on randomly rough terrain. Typically, they focus on the dynamics of various types of vehicles, such as two-axle, three-axle, or multi-axle trucks, as well as the dynamics of tractor-trailer combinations when moving on roads with randomly rough or controlled roughness profiles. These studies often have numerous publications and aim at two main objectives. Firstly, to investigate the influence of road surface profiles on the oscillation of vehicles or structures attached to the vehicle body during movement. Secondly, to propose control strategies to impact the suspension system, aiming to enhance ride comfort during vehicle movement. The two-axle vehicle model is the simplest basic model for studying the oscillations of automobiles. A 7-degree-of-freedom two-axle vehicle model when moving on sinusoidal rough road surfaces is presented to examine the vehicle's response to road stimuli and propose improvements to the original suspension system by introducing a nonlinear suspension system to minimize the impact of road-induced vibrations on the vehicle [1, 2]. In [3], the authors also studied a 3D model of a 7-degree-of-freedom two-axle vehicle with road-induced stimuli from randomly rough road surfaces simulated using Matlab/Simulink software. The authors investigated the vehicle's oscillations under various conditions, including changes in suspension stiffness and vehicle speed. Research on the influence of load distribution and the structural characteristics of the vehicle chassis on vehicle movement is presented in documents [4–6]. In [4], the authors examined a 2D two-axle vehicle model with load distribution along the entire length of the vehicle at a constant speed, evaluating the impact of random road surfaces, stiffness, and damping coefficients of suspension on vehicle oscillations. An analysis of the effects of longitudinal powertrain layout parameters of trucks on vehicle and driver vibrations is presented in [5, 6]. A study focusing on the use of advanced suspension systems to mitigate oscillations during movement, driver comfort, and handling performance for two-axle mining vehicles was conducted in [7]. Similar studies on the dynamics of two-axle vehicles to propose control strategies to improve ride comfort are presented in [8]. Dynamic studies of automobile vehicles to propose control strategies impacting the vehicle's suspension system or cabin suspension are also conducted in documents [9–12]. The 2D or 3D models studying the dynamics of three-axle trucks during movement are presented in documents [13–17]. Research in [14] presents a 3D 11-degree-of-freedom model to examine the influence of vertical oscillations on the driver. In [15], the author developed a 10-degree-of-freedom dynamic model of an automobile to investigate the effects of various parameters in all suspension systems of the vehicle, such as the stiffness and damping of the seat suspension, cabin suspension, vehicle suspension, and wheel suspension, on the oscillation of the driver's seat in both vertical and cabin tilt directions. Dynamic models of four-axle or five-axle trucks are also studied in documents [18, 19]. In these studies, the authors investigated the effects of vibrations during truck movement on randomly rough road surfaces. Dynamic studies of automobiles not only consider the oscillations of the vehicle, passengers, or cargo but also examine the impact of the movement process on road surface deterioration [20]. Some of the mentioned studies have addressed control strategies for the suspension system to reduce vibrations and provide greater comfort for the driver. However, more detailed research has been conducted in documents [21–23].

The paper focuses on investigating the influence of random road surface profiles on the oscillation of the towing vehicle and the power generator trailer during movement at different speeds. The purpose of this research is to solve the theoretical problem to verify the positive effects of upgrading the suspension system on generator trailers compared to the original suspension system. The results of the paper serve as a basis for assessing stability during vehicle movement, aiming to improve the suspension system on the power generator trailer to minimize vibrations during movement and simultaneously improve the replacement of the power generator trailer with trailers carrying ammunition, logistical materials, or wounded soldiers on the battlefield.

2. Materials and methods

2. 1. The dynamic model

The dynamic model for studying the oscillation of the mobile repair vehicle towing the power generator trailer is a 2D model. The three-axle truck is connected to the trailer through a support pillow (**Fig. 2**). The movement of the truck will pull the power generator trailer along. The entire system under investigation is placed in a fixed coordinate system *x*O*z* attached to the ground. The ground is considered to be rigid, and any slope is neglected.

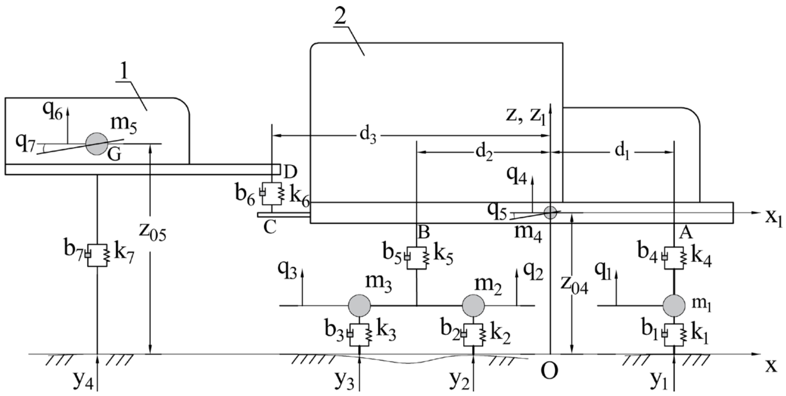


Fig. 2. Dynamic model of the mobile repair vehicle towing the power generator trailer: 1 – the power generator trailer, 2 – the towing vehicle

In **Fig. 2**, m_1, m_2, and m_3 are the masses of the truck axles; m_4 is the mass of the chassis body; and m_5 is the mass of the power generator trailer. The joint connecting the chassis and the power generator trailer is replaced by a spring-damper system with damping coefficient and stiffness denoted as b_6 and k_6, respectively; b_1, b_2, b_3, b_4, b_5, and b_7 are the damping coefficients of the front tire, middle tire, rear tire, front suspension system, rear suspension system, and tire on the power generator trailer, respectively; k_1, k_2, k_3, k_4, k_5, and k_7 are the stiffness of the front tire, middle tire, rear tire, front suspension system, rear suspension system, and tire on the power generator trailer, respectively; d_1, d_2, and d_3 are the distances from the center of mass of the chassis body to the horizontal symmetrical plane of the front suspension system, the distance from the center of mass of the chassis body to the horizontal symmetrical plane of the rear suspension system, and the distance from the center of mass of the chassis body to the axis of the joint, respectively; d_4 is the distance from the center of mass of the power generator trailer to the axis of the joint; J_4 and J_5 are the moments of inertia of the chassis body and the power generator trailer concerning the corresponding rotation axes; z_{01}, z_{02}, z_{03}, z_{04}, and z_{05} are the initial positions of the center of mass of the corresponding masses m_1, m_2, m_3, m_4, and m_5; y_1, y_2, y_3, and y_4 are the road-induced excitation functions acting on the tires, which are considered time-dependent.

The extended coordinate vector for studying the oscillation of the combination is:

$$q = \begin{bmatrix} q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 \end{bmatrix}^T,$$

where q_1 (m), q_2 (m), and q_3 (m) are the displacements of the center of mass of the non-suspended masses on the towing vehicle; q_4 (m) is the vertical displacement of the center of mass of the towing vehicle body; q_5 (rad) is the pitch angle of the towing vehicle body about the axis passing through the center of mass; q_6 (m) is the translation displacement of the center of mass of the power generator combination; q_7 (rad) is the pitch angle of the power generator combination body.

2. 2. The excitation function from the randomly rough road surface

The randomly rough road surface in related studies is determined by two main methods. The experimental method provides high accuracy but is costly. Therefore, many studies have utilized simulation methods based on ISO 8068 standards [24–28]. Accordingly, the road surface with random roughness is divided into eight classes, corresponding to classes A, B, C, D, E, F, G, and H. Using simulation methods, the roughness and height of the road surface can be described depending on the length of the road section or simulated over a time domain.

According to [27, 28], the excitation function from the random rough road surface over the time domain is determined by the expression:

$$\dot{y}(t) + 2\pi f_0 v y(t) = 2\pi n_0 \sqrt{G_q(n_0)} v w(t), \quad (1)$$

where $y(t)$ is the excitation function of the random road surface, $w(t)$ is the white noise sequence, v is the vehicle speed, f_0 is a minimal boundary frequency with a value of 0.0628 Hz, $G_q(n_0)$ is PSD value for reference spatial frequency in m^3. The random rough road profiles of types D and E corresponding to a vehicle speed of 36 km/h are depicted over the time domain as shown in **Fig. 3**.

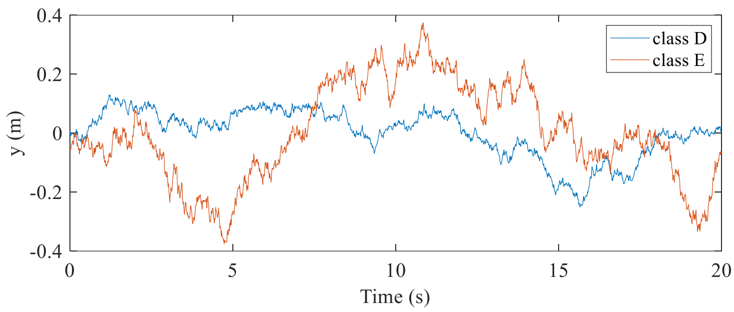


Fig. 3. The random road profile

The maximum amplitude of the class E random road surface occurs when the vehicle travels at a speed of 36 km/h, reaching approximately 38 cm. This indicates a very rough road surface, fairly accurately reflecting the most common terrain conditions that the mobile repair vehicle MTO-AT operates in.

2. 3. Kinetic energy, potential energy and dissipation function

The kinetic energy of the system includes translational kinetic energy and rotational kinetic energy about the central axis passing through the center of masses of the masses m_1, m_2, m_3, m_4, and m_5. The total kinetic energy of the system is determined by the formula:

$$T=\frac{1}{2}m_1\left(v^2+\dot{q}_1^{\,2}\right)+\frac{1}{2}m_2\left(v^2+\dot{q}_2^{\,2}\right)+\frac{1}{2}m_3\left(v^2+\dot{q}_3^{\,2}\right)+\frac{1}{2}m_4\left(v^2+\dot{q}_4^{\,2}\right)+$$
$$+\frac{1}{2}J_4\dot{q}_5^{\,2}+\frac{1}{2}m_5\left(v^2+\dot{q}_6^{\,2}\right)+\frac{1}{2}J_5\dot{q}_7^{\,2}. \tag{2}$$

The total potential energy of the system is determined by the formula:

$$\Pi=m_1g\left(z_{01}+q_1\right)+m_2g\left(z_{02}+q_2\right)+m_3g\left(z_{03}+q_3\right)+m_4g\left(z_{04}+q_4\right)+$$
$$+m_5g\left(z_{05}+q_6\right)+\frac{1}{2}k_1\left(q_1-y_1\right)^2+\frac{1}{2}k_2\left(q_2-y_2\right)^2+\frac{1}{2}k_3\left(q_3-y_3\right)^2+$$
$$+\frac{1}{2}k_4\left(q_4-d_1q_5-q_1\right)^2+\frac{1}{2}k_5\left(q_4+d_2q_5-\frac{q_2+q_3}{2}\right)^2+$$
$$+\frac{1}{2}k_6\left(q_6+d_4q_7-q_4-d_3q_5\right)^2+\frac{1}{2}k_7\left(q_6-y_4\right)^2. \tag{3}$$

The total energy dissipation of the system is determined by the formula:

$$\Phi=\frac{1}{2}b_1\left(\dot{q}_1-\dot{y}_1\right)^2+\frac{1}{2}b_2\left(\dot{q}_2-\dot{y}_2\right)^2+\frac{1}{2}b_3\left(\dot{q}_3-\dot{y}_3\right)^2+\frac{1}{2}b_4\left(\dot{q}_4-d_1\dot{q}_5-\dot{q}_1\right)^2+$$
$$+\frac{1}{2}b_5\left(\dot{q}_4+d_2\dot{q}_5-\frac{\dot{q}_2+\dot{q}_3}{2}\right)^2+\frac{1}{2}b_6\left(\dot{q}_6+d_4\dot{q}_7-\dot{q}_4-d_3\dot{q}_5\right)^2+\frac{1}{2}b_7\left(\dot{q}_6-\dot{y}_4\right)^2. \tag{4}$$

2. 4. The system of differential equations

Applying Lagrange's equations to establish the system of differential equations describing the oscillations of the system, let's obtain the following seven equations:

$$m_1\ddot{q}_1+\left(b_1+b_4\right)\dot{q}_1-b_4\dot{q}_4+b_4d_1\dot{q}_5-b_1\dot{y}_1+\left(k_1+k_4\right)q_1-k_4q_4+k_4d_1q_5-k_1y_1+m_1g=0, \tag{5}$$

$$m_2\ddot{q}_2+\left(b_2+0.25b_5\right)\dot{q}_2+0.25b_5\dot{q}_3-0.5b_5\dot{q}_4-0.5b_5d_2\dot{q}_5-b_2\dot{y}_2+\left(k_2+0.25k_5\right)q_2+$$
$$+0.25k_5q_3-0.5k_5q_4-0.5k_5d_2q_5-k_2y_2+m_2g=0, \tag{6}$$

$$m_3\ddot{q}_3+0.25b_5\dot{q}_2+\left(b_3+0.25b_5\right)\dot{q}_3-0.5b_5\dot{q}_4-0.5b_5d_2\dot{q}_5-b_3\dot{y}_3+0.25k_5q_2+$$
$$+\left(k_3+0.25k_5\right)q_3-0.5k_5q_4-0.5k_5d_2q_5-k_3y_3+m_3g=0, \tag{7}$$

$$m_4\ddot{q}_4-b_4\dot{q}_1-0.5b_5\dot{q}_2-0.5b_5\dot{q}_3+\left(b_4+b_5+b_6\right)\dot{q}_4+\left(b_6d_3-b_4d_1+b_5d_2\right)\dot{q}_5-$$
$$-b_6\dot{q}_6-b_6d_4\dot{q}_7-k_4q_1-0.5k_5q_2-0.5k_5q_3+\left(k_4+k_5+k_6\right)q_4+$$
$$+\left(k_5d_2-k_4d_1+k_6d_3\right)q_5-k_6q_6-k_6d_4q_7+m_4g=0, \tag{8}$$

$$J_4\ddot{q}_5+b_4d_1\dot{q}_1-0.5d_2b_5\dot{q}_2-0.5d_2b_5\dot{q}_3+\left(b_6d_3-b_4d_1+b_5d_2\right)\dot{q}_4+$$
$$+\left(b_6d_3^{\,2}+b_4d_1^{\,2}+b_5d_2^{\,2}\right)\dot{q}_5-b_6d_3\dot{q}_6-d_4d_3b_6\dot{q}_7+k_4d_1q_1-0.5k_5d_2q_2-0.5k_5d_2q_3+$$
$$+\left(k_5d_2-k_4d_1+k_6d_3\right)q_4+\left(k_4d_1^{\,2}+k_5d_2^{\,2}+k_6d_3^{\,2}\right)q_5-k_6d_3q_6-k_6d_3d_4q_7=0, \tag{9}$$

$$m_5\ddot{q}_6-b_6\dot{q}_4-b_6d_3\dot{q}_5+\left(b_6+b_7\right)\dot{q}_6+b_6d_4\dot{q}_7-b_7\dot{y}_4-k_6q_4-k_6d_3q_5+\left(k_6+k_7\right)q_6+$$
$$+k_6d_4q_7-k_7y_4+m_5g=0, \tag{10}$$

$$J_5\ddot{q}_7-b_6d_4\dot{q}_4-b_6d_4d_3\dot{q}_5+b_6d_4\dot{q}_6+b_6d_4^{\,2}\dot{q}_7-k_6d_4q_4-k_6d_4d_3q_5+k_6d_4q_6+k_6d_4^{\,2}q_7=0. \tag{11}$$

The system of differential equations can be represented in matrix form and solved using simulation methods in Matlab software with the following initial conditions:

1) initial displacement:

$$\begin{bmatrix} q_{10} & q_{20} & q_{30} & q_{40} & q_{50} & q_{60} & q_{70} \end{bmatrix}^T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T;$$

2) initial velocity:

$$\begin{bmatrix} \dot{q}_{10} & \dot{q}_{20} & \dot{q}_{30} & \dot{q}_{40} & \dot{q}_{50} & \dot{q}_{60} & \dot{q}_{70} \end{bmatrix}^T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T.$$

The set of input parameters to solve the system is provided in **Table 1** below.

Table 1
Input parameters (All parameters are in SI-units)

Parameter	Value	Parameter	Value	Parameter	Value
k_1, k_2, k_3, k_7	8×10^5	b_5	11500	m_5	1300
k_4	195×10^3	J_4	8250	d_1	2.23
k_5	295×10^3	J_5	230	d_2	1.75
k_6	4×10^5	m_1	305	d_3	3.6
b_1, b_2, b_3, b_6, b_7	500	m_2, m_3	300	d_4	1.2
b_4	24000	m_4	5575	g	9.8

2. 5. Improved suspension system model for power generator trailer

To improve the smoothness of the motion of the power generator trailer, the proposal is to enhance the suspension system of the trailer. Accordingly, the trailer body is suspended on a system of resilient springs with damping coefficients and stiffness coefficients denoted as b_a and k_a, respectively, while the non-suspended mass on the trailer has a mass of m_a (**Fig. 4**). The establishment of the system of differential equations describing the oscillation of the system is conducted similarly to the dynamic model described in **Fig. 2**. It should be noted that, in addition to the seven degrees of freedom presented, q_8 (m) is an additional component introduced to determine the vertical displacement of m_a.

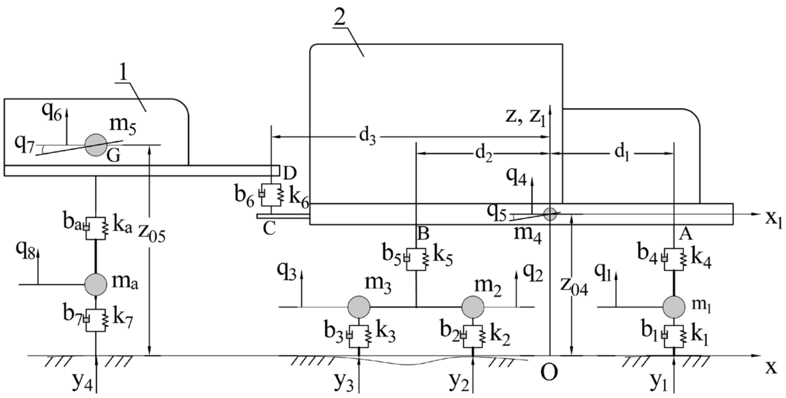


Fig. 4. Improved suspension system model for power generator trailer: 1 – the power generator trailer; 2 – the towing vehicle

Applying the Lagrange equations to establish the system of differential equations describing the oscillation of the system in **Fig. 2**, let's obtain the results consisting of 8 equations. Among them are six equations similar to (5)–(9) and (11). Let's additionally include the following two equations:

$$m_5\ddot{q}_6 - b_6\dot{q}_4 - b_6 d_3\dot{q}_5 + \left(b_6 + b_a\right)\dot{q}_6 + b_6 d_4\dot{q}_7 - b_a\dot{q}_8 - k_6 q_4 - k_6 d_3 q_5 + \\ + \left(k_6 + k_a\right)q_6 + k_6 d_4 q_7 - k_a q_8 + m_5 g = 0, \quad (12)$$

$$m_a\ddot{q}_8 + b_7\dot{q}_8 + k_7 q_8 + m_a g - b_7\dot{y}_4 - k_7 y_4 = 0. \quad (13)$$

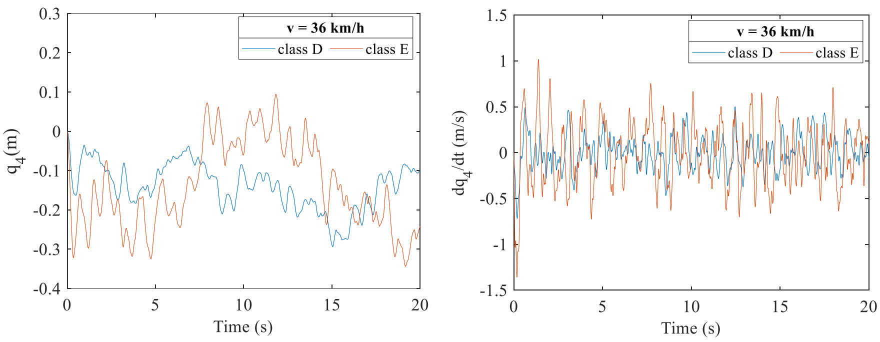
The values of the parameters b_a and k_a are taken as with the front suspension system of the towing vehicle, and the mass $m_a = 250$ kg.

3. Results and discussion

3. 1. The influence of the random roughness of road surfaces in classes D and E

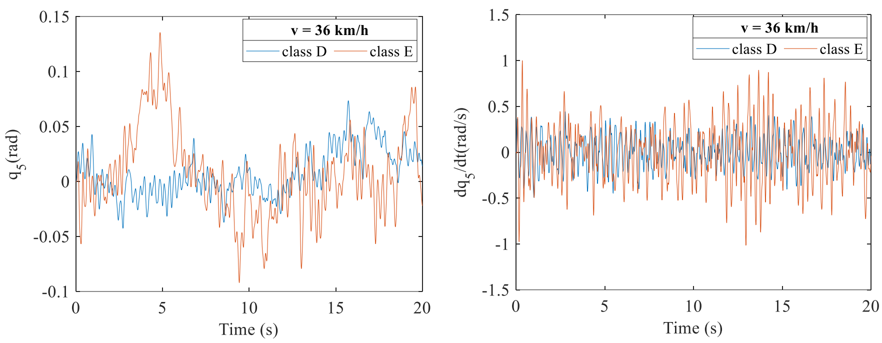
The influence of the random roughness of road surfaces in classes D and E is significant. Class E road surfaces exhibit larger amplitude variations compared to class D surfaces. This difference in roughness directly affects the oscillation behavior of the vehicle and the power generator trailer. Specifically, class E surfaces lead to more pronounced oscillations, resulting in higher pitch angles for both the vehicle and the trailer compared to class D surfaces. This suggests that the roughness of the road surface plays a crucial role in determining the dynamic response of the vehicle-trailer combination. To further evaluate the influence of different types of random road surfaces on the oscillation of the vehicle-trailer combination, it is possible to analyze two conditions: class D and class E road surfaces, with the vehicle moving at a constant speed of 36 km/h. Let's specifically examine how this influence affects the oscillation of both the vehicle chassis and the power generator trailer.

The graphs in **Fig. 5** depict the vertical displacement q_4 and the velocity $\dot{q}_4$ of the vehicle chassis, corresponding to road surfaces of classes D and E. Similarly, the graphs in **Fig. 6** illustrate the angular displacement q_5 and the angular velocity q_5 of the vehicle chassis corresponding to road surfaces of classes D and E. From the graphs in **Fig. 5, 6**, it can be inferred that when moving at the same speed, the chassis of the vehicle oscillates more significantly when traveling on the road surface of class E compared to class D. Consequently, the oscillation velocity of the vehicle chassis is also stronger, with a larger maximum amplitude. Simply put, as the road condition worsens, the vehicle experiences more shocks.



a *b*

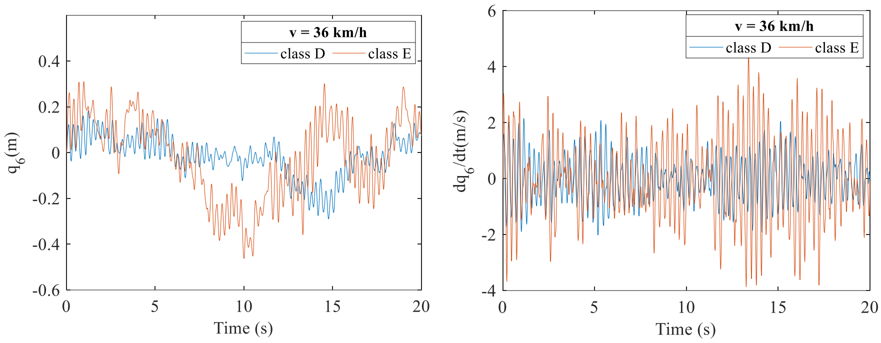
Fig. 5. The chassis's vertical oscillation: *a* – displacement; *b* – velocity



a *b*

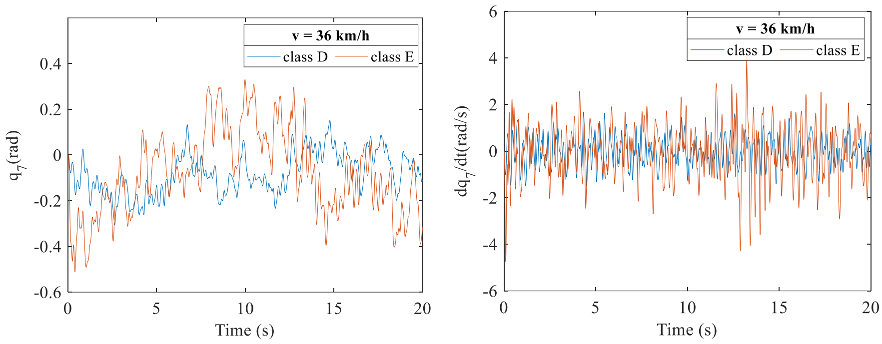
Fig. 6. The chassis's sway oscillation: *a* – the displacement; *b* – the velocity

The oscillation of the generator trailer follows the same pattern as the vehicle chassis oscillation. **Fig. 7, 8** depict the vertical displacement q_6 and velocity q_6, as well as the angular displacement q_7 and angular velocity q_7 of the generator trailer corresponding to road surfaces of classes D and E. Considering the overall oscillation of the generator trailer while simultaneously moving vertically and swaying around the axis passing through the center of mass, as shown in **Fig. 7, 8**, it can be observed that with road surface class E, the oscillation of the generator trailer is stronger, with both displacement and velocity having larger maximum amplitudes compared to road surface class D.



a *b*

Fig. 7. The trailer's vertical oscillation: *a* – displacement; *b* – velocity



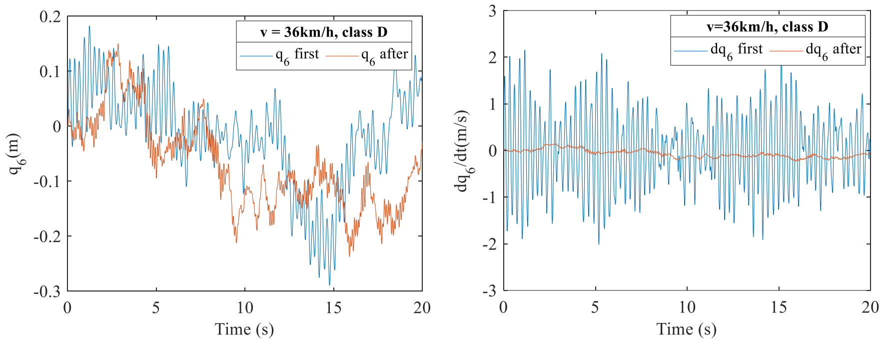
a *b*

Fig. 8. The trailer's sway oscillation: *a* – displacement; *b* – velocity

Considering the pitch angle of the power generator trailer during movement, it is possible to observe that the maximum amplitude is quite significant, around 0.2 rad/s, corresponding to 11.5°, and the angular velocity q_7 also increases as the vehicle speed increases. Examining the overall oscillation of the power generator trailer, it is possible to see that when the vehicle is in motion, the power generator trailer experiences considerable oscillations. The reason for such significant oscillations in the power generator trailer is that it lacks a damping system to dampen the oscillations. In reality, road surface class E represents very poor road conditions with relatively large maximum height variations. Examining the oscillation of both the vehicle chassis and the generator trailer when traveling on road surfaces of classes D and E is relevant in combat scenarios where vehicles traverse hilly terrain. Road surfaces of classes F, G, and H are not considered because, typically, before moving vehicles through such terrain, road repair forces have already worked on the road surface. The response of the mobile repair vehicle towing the generator trailer to terrain with random deformations before improvement is appropriate. In general, the oscillation of the generator trailer is quite intense without a suspension system. To reduce the oscillation of the generator trailer, one option under consideration is to improve the suspension system on the trailer.

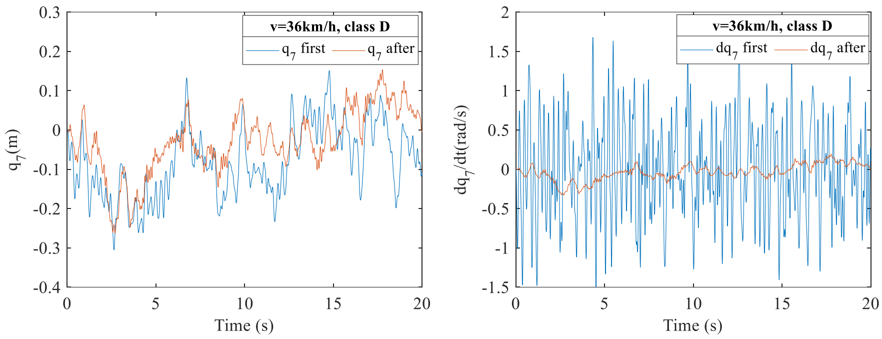
3. 2. The oscillation of the power generator trailer before and after improvement

Before and after upgrading, the oscillations of the generator trailer can be compared in terms of their magnitude and smoothness. Before the upgrade, the trailer may exhibit larger and more erratic oscillations due to its lack of a damping system, resulting in significant sway and vertical movement as it traverses uneven terrain. However, after the upgrade, with improvements to the suspension system, the oscillations are expected to be reduced in magnitude and become smoother, resulting in a more stable and controlled motion of the trailer, especially when encountering rough road conditions. The upgrade aims to minimize unwanted oscillations, enhancing the overall performance and reliability of the generator trailer during transportation. A study was conducted on a power generator trailer moving on a road with random roughness of class D at a speed of 36 km/h, both before and after the suspension system of the trailer was improved. The comparison of the vertical displacement q_6 and the pitch angle q_7 of the trailer is shown in **Fig. 9, 10**, respectively.



a *b*

Fig. 9. The trailer's vertical oscillation when $v = 36$ km/h: *a* – displacement; *b* – velocity



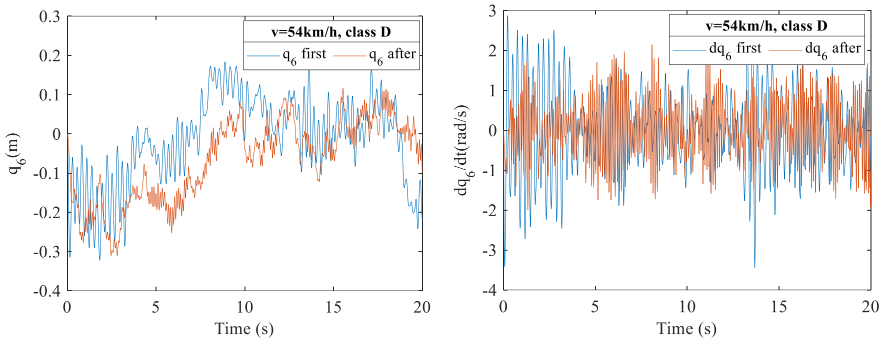
a *b*

Fig. 10. The trailer's sway oscillation when $v = 36$ km/h: *a* – displacement; *b* – velocity

The most noticeable observation is that the maximum amplitude of the displacements q_6 and q_7 significantly decreased after the suspension system of the trailer was improved. The estimated reduction in the maximum amplitude of displacements q_6 and q_7 is approximately 18 %. Correspondingly, the oscillation speed of the trailer also decreased substantially after the improvement. This confirms that the trailer will have smoother motion after the suspension system is improved.

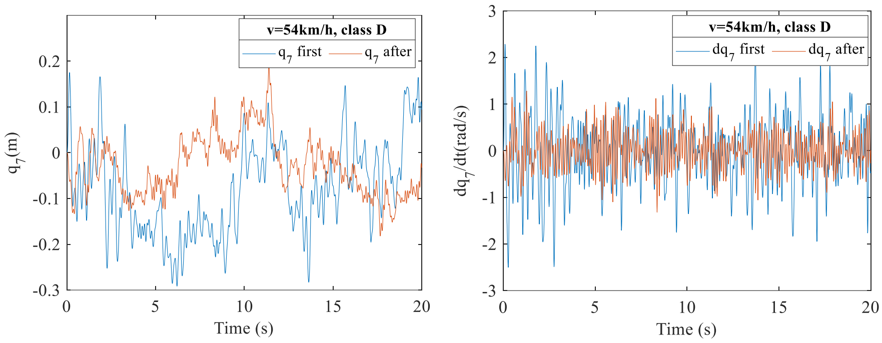
In the case of the vehicle moving on a road with random roughness of class D at a speed of 54 km/h, both before and after improving the suspension system of the power generator trailer, the comparison of the vertical displacement q_6 of the trailer is shown in **Fig. 11**, and the comparison of the pitch angle q_7 of the trailer is shown in **Fig. 12**. When moving at a speed of 54 km/h, the maximum amplitudes of q_6 and q_7 have also decreased after improving the suspension system of the power generator trailer. The oscillation speeds q_6 and q_7 also exhibit a decrease in maximum amplitude. Specifically, q_6 decreased by approximately 43 % and q_7 by about 40 %.

Comparing the speeds q_6 and q_7 of the trailer after improvement, corresponding to speeds of 36 km/h and 54 km/h, it is observed that as the vehicle moves faster, the oscillation speeds also increase significantly. Therefore, a preliminary recommendation could be to operate the vehicle at lower speeds under normal conditions.



a *b*

Fig. 11. The trailer's vertical oscillation when $v = 54$ km/h: *a* – displacement; *b* – velocity



a *b*

Fig. 12. The trailer's sway oscillation when $v = 54$ km/h: *a* – displacement; *b* – velocity

3. 3. Limitations of the research and directions for its further development

In this research, the model has only been developed in a 2D model. Consequently, the influence of rough road surfaces on the movement of the mobile repair vehicle has not been comprehensively considered. To fully examine the impact of the road surface, the theoretical study of the dynamics of the mobile repair vehicle should continue in a 3D model. In this scenario, road surface irregularities affect the tires independently according to different excitation functions. The use of ISO 8068 standards to describe road roughness is also less accurate than conducting experiments. To apply this research to practical situations, the theoretical study of the dynamics of this vehicle assembly in a 3D model must continue, with the road surface excitation function being one of the key input variables measured experimentally on real terrain to ensure it closely matches the actual usage conditions of the assembly. The practical application scope of this research is somewhat limited as it mainly pertains to military mobile repair vehicle assemblies. However, the theoretical study provides a reference foundation for the study of vehicle dynamics in general when moving over randomly rough road surfaces. This research should be further conducted in more depth to comprehensively investigate the influence of the structure and dynamic parameters of the suspension system on the power generator trailer after improvement, aiming to identify a set of reasonable operating parameters.

4. Conclusions

This study investigated the impact of various types of random road surfaces on the oscillation of a mobile repair vehicle towing a power generator trailer before and after improving the suspension system on the trailer. When considering the influence of different types of random road surfaces on the oscillation of the combination before improvement, it can be confirmed that rougher road surfaces lead to stronger vehicle oscillations, especially affecting the power generator trailer.

For the case of controlling the combination to move forward on the same type of road surface with speeds 36 km/h and 54 km/h, the research results indicate that it is advisable to maintain the vehicle speed at a lower level because the oscillation amplitudes of both the base vehicle and the power generator trailer tend to reach smaller maximum values. After improving the suspension system on the power generator trailer, the results show that the power generator trailer moves more smoothly compared to before the improvement, with the oscillation amplitude reduced by approximately 18 % and the maximum oscillation speed reduced by up to 40 %. The research results provide a basis to assert that the suspension system on the power generator trailer can indeed be improved in practice.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgements

The authors would like to thank the Le Quy Don Technical University and University of Transport Technology for giving us the opportunity to conduct this research.

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Received date 10.05.2024
Accepted date 17.07.2024
Published date 10.09.2024

How to cite: *Dao Manh Quyen, Tran Duc Thang, Le Van Duong (2024). Study on terrain response of the military mobile repair vehicle towing power generator trailer before and after improvement. EUREKA: Physics and Engineering, 5, 3–14. https://doi.org/10.21303/2461-4262.2024.003384*