Investigations On An Influence Of The Material Properties On Vibrations Of Active Rocker-Boogie Suspension

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Abstract. Unmanned vehicles are often used in everyday life, mostly by rescue teams or scientist during exploration of new terrains. In those constructions suspension has constant dimensions what leads to many disadvantages and more over limits application area. The solution of these problems can be a creation of a six – wheeled mobile platform which can dynamically change wheel base in relation to the area of action or terrain inclination angle. The active change in location of center of gravity gives a possibility to access sloppy obstacles not available with classical suspensions. The main scope of this study is to investigate an influence of material properties on vibration frequency at different length of suspension members. The obtained results will allow finding the optimum material for production of a prototype unit.

Key words: frequency analysis, suspension, rover, mobile platform, computational mechanics

1. INTRODUCTION

Over the years, unmanned, autonomous and remote-controlled vehicles have become very popular [1]. These types of robots can often take part in missions and tasks in which a man must risk own life or health. Robots are also often used to replace people in tasks that are burdensome for them. However, they have their drawbacks such as the fundamental algorithmic limitations on what a set of autonomous mobile robots can or cannot achieve what was widely discussed in [2]. Scientific publication on rovers can be devoted into two types in relation to the used type of drive system. In the first one rovers use track drives [3] (not discussed in this paper), while in the second type one uses regular wheels. Implementation of wheels as elements responsible for motion of the rover requires the design of suspension system. Among the land-moving mobile platforms, one can distinguish several suspension systems. In the literature one can find studies on wheel-legged robots. They often run on four wheels. This construction is interesting due to fact that in can move on wheels or walk. In [4] it was shown that the moving on wheels and walking modes are an effective way of moving in difficult terrain conditions. In paper [5], Authors have used velocity based algorithm in order to improve traction and performances of a reconfigurable rover. On the basis of results of many simulations the correctness of this approach was stated. In [6, 7] Authors have focused on testing an influence of the wheel legged construction on keeping main platform in horizontal position. In must be mentioned that the proposed construction passed all tests successfully. The main pros about wheel-legged robots are combined possibilities of moving on wheels and walking. On the cons side one should mention about slow walking and hard to implement autonomous moving – walking algorithms.

The next used suspension system is a multi-link suspension system – [8]. It is simple in design where each wheel is suspended separately. On the pros side one can find that even at mechanical failure of one of the suspension units, the vehicle is not immobilized, which increases the reliability of the whole structure. The disadvantage of this type of construction is that it consists of many parts, which increases production and possible service costs. Additionally, with this suspension system, a vehicle approaching a vertical obstacle is only able to overcome it when it is not greater than twice the wheel diameter.

The next presented type of suspension is the bogie type [9] – see Fig. 1. It uses six wheels are two swingarms on each side. Thanks to this solution, the use of additional elements like differential bars is not required because of presence of two support axes of the rover's frame. The advantage of this suspension is that it can move at a much higher speed than the for example rocker-bogie system, and in the case of collision with an obstacle, it has greater stability and strength due to the support of the frame on two axes. Besides, the structure itself...
is also more rigid. The downside to this suspension is that the front wishbones must have a pivot angle limitation and the weight distribution to wheels is uneven.

![Bogie suspension](image1)

**Fig. 1. Bogie suspension**

The rocker–bogie suspension (Fig. 2, [10 – 12]) has construction partly similar to the bogie suspension, but it has some significant differences and combines both solutions presented above. It is currently used in "Opportunity" and "Curiosity" rovers, which are on Mars. It consists in the fact that the left and right wheels of the rover are connected by a differential bar, thanks to which they remain in constant contact with the ground, even when one of the wheels drives over a boulder equal to the length of the wheelbase. In practice, it looks like that if one tilts the front right wheel by the angle α upwards, the front left wheel will tilt by the same angle downwards, maintaining the average angle of inclination of the frame concerning both wishbones. Additionally, the rocker-bogie construction does not contain springs. As with any suspension system, stability on steep climbs is limited by the height of the center of gravity. Based on the center of mass, this suspension can withstand a slope of at least 45 degrees in any direction without tipping over.

![Rocker bogie suspension at work](image2)

**Fig. 2. Rocker bogie suspension at work**

To overcome the vertical obstacle, the front wheels are pressed against the obstacle by the middle and rear wheels. The rotation of the front wheel raises the front of the vehicle above the obstacle. The center wheel is then pressed against the obstruction by the rear wheel and pulled against the obstruction by the front until it is lifted. Finally, the rear wheels are pulled onto the obstacle by the two front wheels. Over the years Authors of this paper have developed mobile platforms in different configurations. The first one [9] was the one with bogie suspension type which was used in University Rover Challenge (URC) and took 6th place in 2015. Next configuration used rocker bogie suspension [12] made of cylindrical profiles. This construction was very successful and won URC in 2018. Due to great dimensions, problematic transport to USA and high slenderness of suspension members it was decided that an evolution of used suspension is required. In 2021 the active rocker boogie suspension was finally created. The first studies on new configurations (active rocker – bogie system) were presented in [13]. Separate path of studies [14] were ones devoted to manipulator used in URC challenges. In this paper design and results of FEA static analysis were discussed. When choosing a suspension system, it is important to consider what the vehicle is intended for. Because each of the suspensions has its pros and cons, and there isn’t one that is best. One often has to take into account the budget and the assumptions set by the regulations of the competition or project, according to which the vehicle will be created. It is also worth to mention that frames of rovers are usually based on the simplest shapes and resemble cubic solids, the purpose of which is to connect the individual driving modules stably. They also need to house electronics, batteries or other alternative power sources inside the vehicle. These vehicles, apart from good driving properties in difficult terrain and specific conditions, must also fulfill other tasks, for which they often need additional equipment. These include manipulators, special measuring devices and containers for transporting dangerous goods, radars, and scanners – [15]. This gives a challenge to the constructors in which they have to face the combination of all these components into one vehicle – [14, 16 - 17].

As mentioned earlier the mobile platform presented in this paper has a unique rocker – boogie suspension which can change the distance between the external axles. Suspension units can modify their length as desired changing the suspension from symmetrical into unsymmetrical one. This solution gives a possibility to control the location of the center of gravity when platform is driven on very sloppy obstacles which can have different inclinations on each side of the rover. The sample of the results on this type of engineering solution was discussed in [13], where Authors studied an influence of material type on endurance of active rocker-boogie suspension. The main task of this paper is to discuss an influence of the material properties on durability, vibrations and vibration modes of suspension system when Aluminum 6060 T66, Steel S235 or Titanium grade 1 are used. The choice of these materials is dictated by a wide range of profiles and their easy accessibility. The studies are done at different suspension length.

2. DESCRIPTION OF THE TESTED SYSTEM

The subject of the research is a semi-autonomous mobile platform, which is equipped with a unique and so far unprecedented suspension system. It is a mechanical system partly based on a rocker-bogie suspension. The tested system is able to dynamically change its height and the wheelbase.
During action in the variable terrain conditions – see Fig. 3 and Fig. 4.

The advantage of this arrangement is that the vehicle can increase the wheelbase and height by more than 100% relative to its original dimensions. Often, with this type of unconventional vehicle, such as Martian rovers or military robots for special tasks, an important role is played by the amount of space taken up in transport, a flight to another planet, or even transport in a car or a pallet. Thanks to this solution, the platform does not need to be disassembled and is ready for operation at any time. However, if the operator decides that an increase in platform dimensions in needed, it can done remotely at any time.

In the planned prototype construction (Fig. 5) the location of the center of gravity thereby length of suspension members will change dynamically on the basis of data from accelerometers and the gyroscope. Due to the fact of change in length of suspension members one has to consider the change in their slenderness what will greatly affect durability, stress and displacement magnitude as well as vibration frequency of the structure. The general view on the change in length of suspension members is given Fig. 6.

The length of the individual suspension members is adjusted by a gear motor connected to a belt transmission that drives the trapezoidal screw that converts the rotary motion into a linear motion. To simplify the calculation model, these elements have been removed from the assembly because they have a negligible effect on the final results and significantly complicate the meshing process and further calculations.

3. DESCRIPTION OF THE CALCULATION MODEL

Before creating the design, several assumptions were made that were guided during the construction:
- outer wheelbase not greater than 1000mm,
- initial wheelbase from 500mm up to 1000mm,
- total mass of the frame and suspension units less than 30kg (with motors, wheels, and electronic equipment but without manipulator).

The above assumptions were also based on the rules of the URC competition [18], in which the robot will be tested. Besides, the suspension model has been simplified for calculations in such a way that it does not affect the analysis results (drive sets and pivot pins between the arms have been removed).

The studies were performed according to the following workflow (Fig. 7):
In every case of problem involving linear elastic material one can define the matrix equation of motion which in the generalized form can be written as:

\[
[M][\ddot{U}] + [C][\dot{U}] + [K][U] = [F]
\]

(1)

where: \( M \) – mass matrix, \( U \) – displacement, \( \ddot{U} \) – 2nd time derivative of displacement \( U \), \( C \) – damping matrix, \( \dot{U} \) – velocity, \( K \) – stiffness matrix, \( F \) – force vector. In the modal analysis problems the above equation is being reduced to:

\[
[M][\ddot{U}] + [K][U] = 0
\]

(2)

due to generally ignored damping. In order to solve free vibration task it is assumed that, where is an eigenvalue. This converts (2) into (3)

\[
[M][U] + [K][U] = 0
\]

(3)

where \( \omega \) is vibration frequency. The above gives the general form of the eigensystem which is widely used by engineers during FEM simulations. On the basis of (3) the FEM solvers implemented in the CAD software like Catia or Solidworks allows one to calculate vibration frequencies as well as vibration modes. The detailed description of FEM along with mathematical deductions can be found in [19].

In this study nine calculation models have been prepared for the frequency analysis: 3 for each of the selected materials: PA11 aluminum alloy, S235 steel, and grade 1 titanium. Each material was studied in three scenarios: the first - when suspension system is fully extended, the second - suspension is half-folded, and the third - fully folded.

Simulations were performed in SolidWorks software where cannot consider friction between suspension parts in the studied cases. A uniform solid mesh with an element size of 5 mm and a tolerance of 0.25 mm was applied to the model. The mesh was selected experimentally to obtain the appropriate shape mapping. The percentage of elements with an aspect ratio less than 3 is 96%, and the percentage of elements with an aspect ratio greater than 10 is 0.04% [20]. This mesh consists of 419535 elements, 760884 nodes and 2261466 DOF. In the places of the pins connecting the rocker arms, a virtual pin connection was used (notation 1 in Fig. 8). In the places where the drive units are mounted, all degrees of freedom (translations and rotations) have been removed (notation 2 in Fig. 8). It was assumed that the vehicle is stationary and in this state all engines have the brakes applied.

![Figure 8](image.png)

**Fig.8. The mesh is superimposed on the model**

**4. NUMERICAL SIMULATIONS**

For each of the discussed scenarios, frequency studies were conducted. In each case, the first three modes of vibration were taken into account. The used material data are given in Table 1.

**Table 1.** Material properties of the considered materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Unit</th>
<th>Aluminium 6060 T66</th>
<th>Steel S235</th>
<th>Titanium grade 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength</td>
<td>[N/m²]</td>
<td>1.60·10⁸</td>
<td>2.35·10⁸</td>
<td>2.2·10⁸</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>[N/m²]</td>
<td>1.70·10⁸</td>
<td>3.6·10⁸</td>
<td>3.45·10⁸</td>
</tr>
<tr>
<td>Longitudinal elasticity modulus</td>
<td>[N/m²]</td>
<td>6.95·10¹⁰</td>
<td>2.1·10¹¹</td>
<td>1.05·10¹¹</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>-</td>
<td>0.33</td>
<td>0.28</td>
<td>0.34</td>
</tr>
<tr>
<td>Density</td>
<td>[kg/m³]</td>
<td>2700</td>
<td>7800</td>
<td>4510</td>
</tr>
<tr>
<td>Construction mass</td>
<td>[kg]</td>
<td>15.187</td>
<td>31.775</td>
<td>20.937</td>
</tr>
</tbody>
</table>

Although construction mass made of steel exceeds 30 kg it is worth to give it a try due to fact of low production cost and easy manufacturing what can reward time spend on additional mass optimization. First part of results is devoted to vibration modes. In order to achieve better visualization, on the obtained modes of vibrations, a translucent model at rest was superimposed. At the beginning it should be...
Investigations on an influence of the material properties on vibrations of active Rocker-Boogie suspension

mentioned that regardless to used material the similar vibration modes were found for other studied materials but due to limited space are not printed. The Figs. 9 – 11 present the results for studies with the use of Aluminum. The similar vibration modes were found for other studied materials.

As presented in the Fig. 9 (at suspension full length) the first vibration mode (a) makes the construction to shake for side to side making the swing arms mounting points to be the most loaded. The points at which one also should take care of are the differential bar mountings slots. When the second vibration mode (b) is taken into consideration, one can observe it in plane perpendicular to the longitudinal axis of the rover. The most loaded part of the platform is now the differential bar and electronic equipment box. An increase in differential bar stiffness should be considered as this element is crucial for proper rocker – bogie suspension operation. In the third case (c) the special observation of suspension members should be done. Especially correct installation and stiffness of sliding elements thanks to which suspension members can move freely up and down. At great
displacements the screw drive system used to change suspension length can also be damaged. Lowering the suspension to the half of total length or lower shows that first and second vibration modes are very similar to the previously discussed. But the third vibration mode plotted in the Fig. 10c and Fig. 11c shows the change in vibration mode in relation to Fig. 9c. Now, the most loaded parts are areas of installation of electric engines used for suspension operation. An addition of small stiffening elements which should reduce the possibility of crack appearance should be taken into account. As presented the change in length of suspension member greatly affects the vibration modes what results in the change of the most loaded elements. As it was mentioned before the change in length of suspension members changes their slenderness factor. The longer the element the lower slenderness while at the same time lower durability and higher total displacements and reduction in frequency of vibrations. In the graphs below (Figs. 12 – 14) one has plotted the relationship between length of suspension members and vibration frequency.

The vibration frequency magnitude is being reduced along with an increase in length of suspension member. This change is similar at all studied materials. As the first vibration frequency is discussed one can see that the greatest vibration frequency reduction is obtained between 506 – 630 mm length of suspension members. It is worth to mention that with further increase in length of members the small increase/reduction in vibration frequency can be observed. Above 830 mm the vibration frequency has the lowest magnitudes. When the second vibration frequency is observed, it can be concluded that the most rapid reduction in vibration frequency is observed between 506 – 610 mm. Length above 610 mm has the smallest influence on vibration frequency from all studied curves. When the third vibration frequency in concerned one can summarized that an influence of suspension length on vibration frequency has the same tendency as at the first one but at greater ablative value. The differences between first highest and lowest vibration frequency are as follows: Aluminum – 307.27 Hz, Steel – 297.33 Hz, Titanium – 280.13 Hz. Similar order of materials (highest – lowest frequency) can be found for second and third vibration frequencies.

5. Conclusions

In this paper an influence of material properties on vibration frequency of an active rocker – bogie suspension has been discussed. The materials such as Aluminum, Steel and Titanium Grade 1 have been taken into consideration. It can be concluded that the most suitable material is Aluminum due to greatest differences in vibration frequency what results in great operating range during terrain actions as well as the non-problematic prototype production. However, as presented in section 4 one should consider an introduction of more durable elements like differential bar which can be changed to one made of carbon fiber material what will save few grams or redesigning electric engines installation places. Titanium offers also good operating range but at much greater cost and can be a good option if Aluminum construction will fail during terrain tests. An interesting option in future simulation plan is a hybrid construction made of Titanium and Aluminum. The Steel in not worth of consideration due to lowest vibration range which is will not balance the time spent on mass optimization (total mass is...
almost 1.8 kg greater than required). In the future further studies should be done in which one will test an influence of material properties on construction durability and vibration frequency at different length of each of suspension members what will simulate motion on sloped terrain like driveways, ditches or raps. Also change in profiles type from rectangular into for example cylindrical should be discussed in order to find optimum solution.

REFERENCES