Investigations on an influence of the material properties on vibrations of active rocker-bogie suspension

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Abstract. Unmanned vehicles are often used in everyday life, mostly by rescue teams or scientists exploring new terrains. In those constructions, the suspension has constant dimensions, which leads to many disadvantages and limits the application area. The solution to these problems can be creating a six-wheeled mobile platform that can dynamically change the wheelbase in relation to the area of action or terrain inclination angle. The active change in location of the center of gravity gives a possibility to access sloppy obstacles not available with classical suspensions. The main scope of this study is to investigate the influence of material properties on vibration frequency at different lengths of suspension members. The obtained results will allow finding the optimum material for producing 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 robots can often take part in missions and tasks in which a man must risk his own life or health. Robots are also often used to replace people in burdensome tasks. However, they have drawbacks, such as the fundamental algorithmic limitations on what a set of autonomous mobile robots can or cannot achieve, as was widely discussed in [2].

Scientific publications on rovers can be divided into two types related to the used type of drive system. In the first one, rovers use track drives [3] (not discussed in this paper), while the second type uses regular wheels. Implementation of wheels as elements responsible for the rover's motion requires the design of a 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 because it can move on wheels or walk. In [4], it was shown that moving on wheels and walking modes are an effective way of moving in difficult terrain conditions. In paper [5], the authors have used a velocity-based algorithm to improve the traction and performances of a reconfigurable rover. Based on the results of many simulations, the correctness of this approach was stated. In [6, 7], authors have focused on testing the influence of the wheel-legged construction on keeping the main platform in a horizontal position. It must be mentioned that the proposed construction passed all tests successfully. The main

pros of wheel-legged robots are the combined possibilities of moving on wheels and walking. One should mention slow walking and hard to implement autonomous moving – walking algorithms on the cons side.

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 a 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 can only overcome it when it is not greater than twice the wheel diameter.

The next presented suspension type is the bogie type [9] – see Fig. 1. It uses six wheels are two swingarms on each side. Thanks to this solution, additional elements like differential bars are not required because of the presence of two support axes of the rover's frame. The advantage of this suspension is

Fig. 1. Bogie suspension

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that it can move at a much higher speed than the rocker-bogie system, and in the case of a 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 uneven weight distribution to wheels.

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 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.
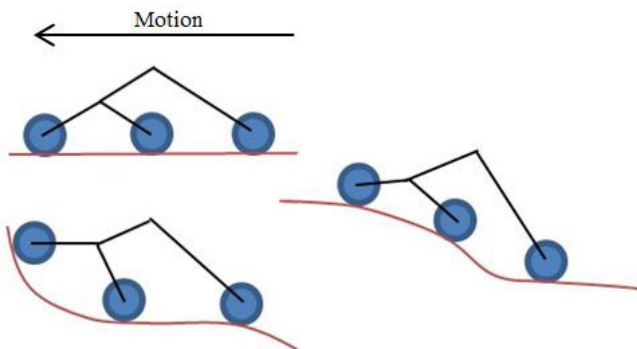

Fig. 2. Rocker-bogie suspension at work

The front wheels are pressed against the obstacle by the middle and rear wheels to overcome the vertical obstacle. The front wheel's rotation 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 two front wheels pull the rear wheels onto the obstacle.

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. The 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 the USA and high slenderness of suspension members, it was decided that evolution of used suspension is required. In 2021 the active rocker-bogie suspension was finally created.

The first studies on new configurations (active rocker-bogie system) were presented in [13]. A separate path of studies [14] was devoted to manipulators 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 suspension has its pros and cons, there is not the best one. One often has to consider 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 mentioning that rovers' frames 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. Apart from good driving properties in difficult terrain and specific conditions, these vehicles must also fulfil 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-bogie suspension that can change the distance between the external axles. Suspension units can modify their length as desired, changing the suspension from symmetrical to unsymmetrical. This solution gives a possibility to control the location of the center of gravity when the 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 engineering solution was discussed in [13], where authors studied the influence of material type on the endurance of active rocker-bogie suspension. The main task of this paper is to discuss the influence of the material properties on durability, vibrations and vibration modes of the 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 lengths.

2. DESCRIPTION OF THE TESTED SYSTEM

The research subject is a semi-autonomous mobile platform, which is equipped with a unique and unprecedented suspension system. It is a mechanical system partly based on a rocker-bogie suspension. The tested system can 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 is needed, it can be done remotely.
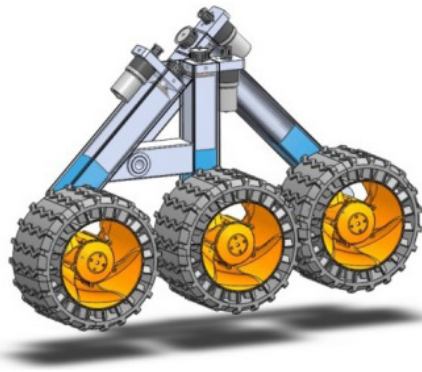
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Fig. 3. One side of the suspension in the fully folded position
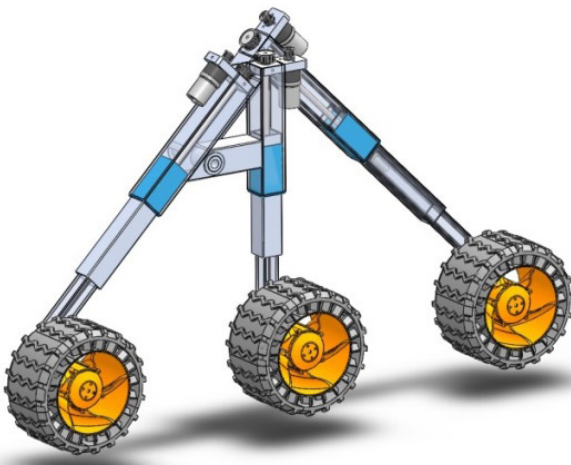

Fig. 4. One side of the suspension in the fully extended position

In the planned prototype construction (Fig. 5) the location of the center of gravity, thereby the length of suspension members, will change dynamically based on data from accelerome-
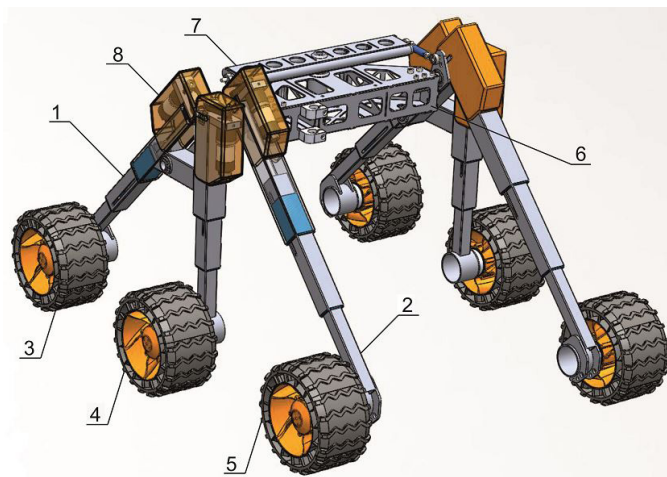

Fig. 5. Main components of the prototype construction: 1, 2 – suspension arms; 3, 4, 5 – wheels with electric motors; 6 – main frame; 7 – differential bar; 8 – electric motors for suspension control

ters and the gyroscope. Due to the change in length of suspension members, one has to consider the change in their slenderness, which will greatly affect durability, stress and displacement magnitude, and vibration frequency of the structure. The general view on the change in length of suspension members is given in Fig. 6.
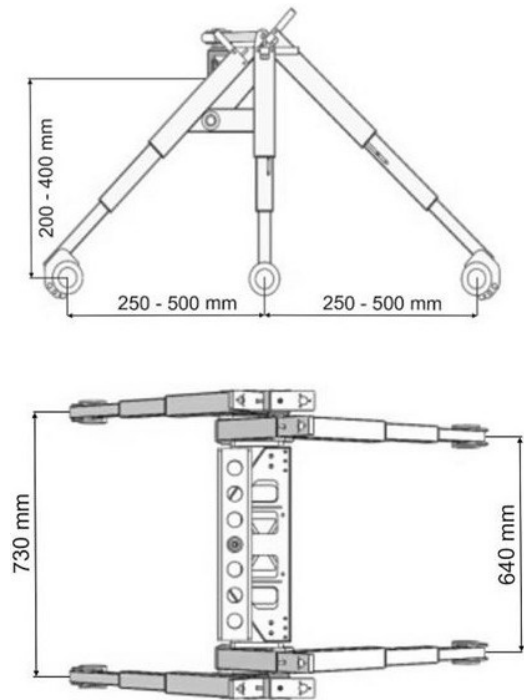

Fig. 6. Dimensions of the tested suspension system

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. These elements have been removed from the assembly to simplify the calculation model 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 1000 mm,
- initial wheelbase from 500mm up to 1000 mm,
- 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 so that it does not affect the analysis results (drive sets and pivot pins between the arms have been removed).

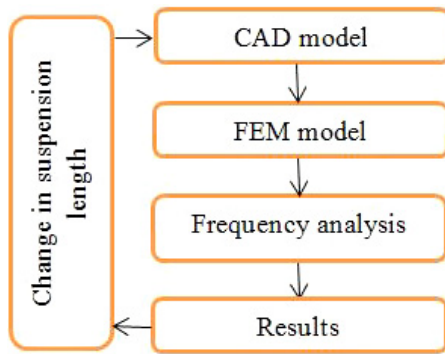The studies were performed according to the following workflow (Fig. 7).

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Fig. 7. Research methodology

In every case of problem involving elastic liner material one can define the matrix equation of motion, which in the generalized form can be written as:

$$[M][\ddot{U}] + [C][\dot{U}] + [K][U] = [F], \tag{1}$$

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

$$[M][\ddot{U}] + [K][U] = 0 \tag{2}$$

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

$$[M][U]\omega + [K][U] = 0, \tag{3}$$

where ω is vibration frequency. The above gives the general form of the eigensystem, which engineers widely use during FEM simulations. Based on (3) the FEM solvers implemented in the CAD software like Catia or Solidworks allow one to calculate vibration frequencies and vibration modes. A detailed description of FEM and mathematical deductions can be found in [19].

This study has prepared nine calculation models 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 the 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 of less than 3 is 96%, and the percentage with an aspect ratio greater than 10 is 0.04% [20]. This mesh consists of 419535 elements, 760884 nodes and 2261466 DOF. A virtual pin connection was used in the pins connecting the rocker arms (notation 1 in Fig. 8). In the places where the drive units are mounted, all degrees of freedom (translations and rotations) have been re-

moved (notation 2 in Fig. 8). It was assumed that the vehicle is stationary, and in this state, all engines have the brakes applied.
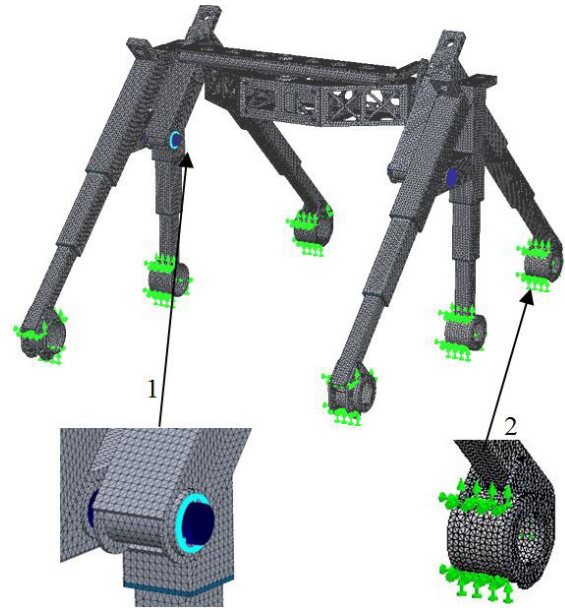

Fig. 8. The mesh is superimposed on the model

4. NUMERICAL SIMULATIONS

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

Table 1
Material properties of the considered materials

Material	Unit	Aluminum 6060 T66	Steel S235	Titanium grade 1
Yield strength	[N/m²]	$1.60 \cdot 10^8$	$2.35 \cdot 10^8$	$2.2 \cdot 10^8$
Tensile strength	[N/m²]	$1.70 \cdot 10^8$	$3.6 \cdot 10^8$	$3.45 \cdot 10^8$
Longitudinal elasticity modulus	[N/m²]	$6.95 \cdot 10^{10}$	$2.1 \cdot 10^{11}$	$1.05 \cdot 10^{11}$
Poisson ration	–	0.33	0.28	0.34
Density	[kg/m³]	2700	7800	4510
Construction mass	[kg]	15.187	31.775	20.937

Although construction mass made of steel exceeds 30 kg, it is worth giving it a try due to low production cost and easy manufacturing what can reward time spent on additional mass optimization. The first part of the results is devoted to vibration modes. To achieve better visualization of the obtained modes of vibrations, a translucent model at rest was superimposed. In the beginning, it should be mentioned that regardless of the used material, similar vibration modes were found for other studied materials but are not printed due to limited space. Figures 9–11 present the results for studies using aluminum. Similar vibration modes were found for other studied materials.

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Fig. 9. Vibration modes – a construction made of aluminum with the full length of suspension; mode 1 – a), mode 2 – b), mode 3 – c)
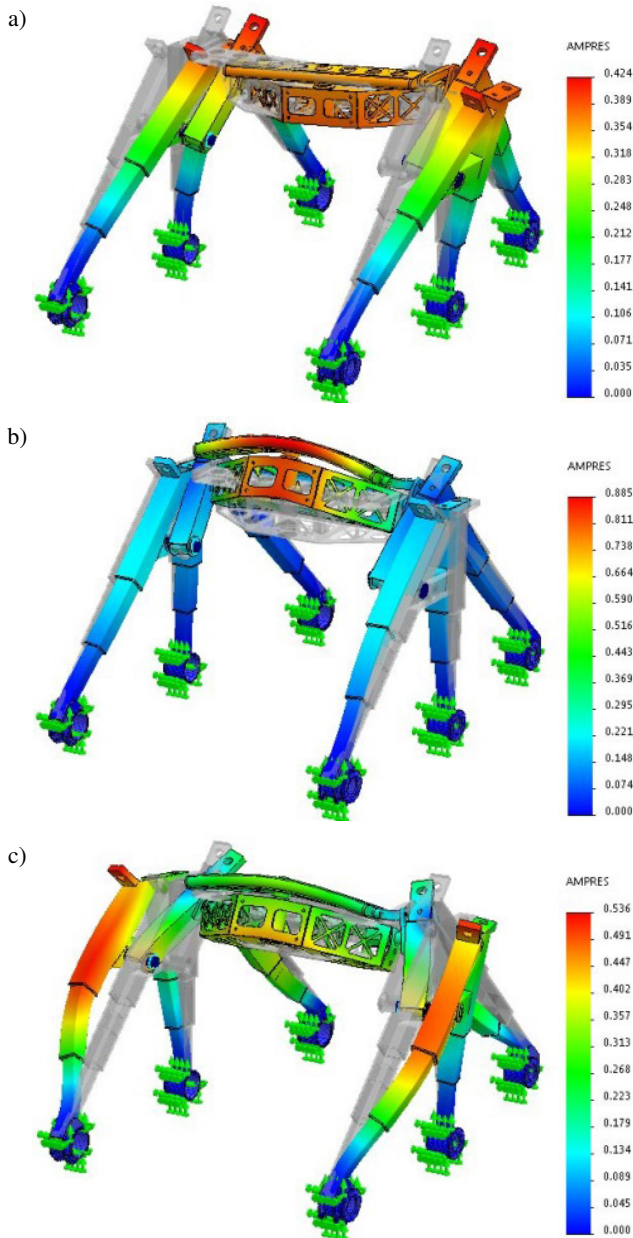

Fig. 10. Vibration modes – a construction made of aluminum with half of the total length of suspension; mode 1 – a), mode 2 – b), mode 3 – c)

As presented in Fig. 9 (at full suspension length), the first vibration mode (a) makes the construction shake from side to side, making the swing arms mounting points the most loaded. The points that one should also take care of are the differential bar mountings slots. When the second vibration mode (b) is considered, one can observe it in a 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. The screw drive
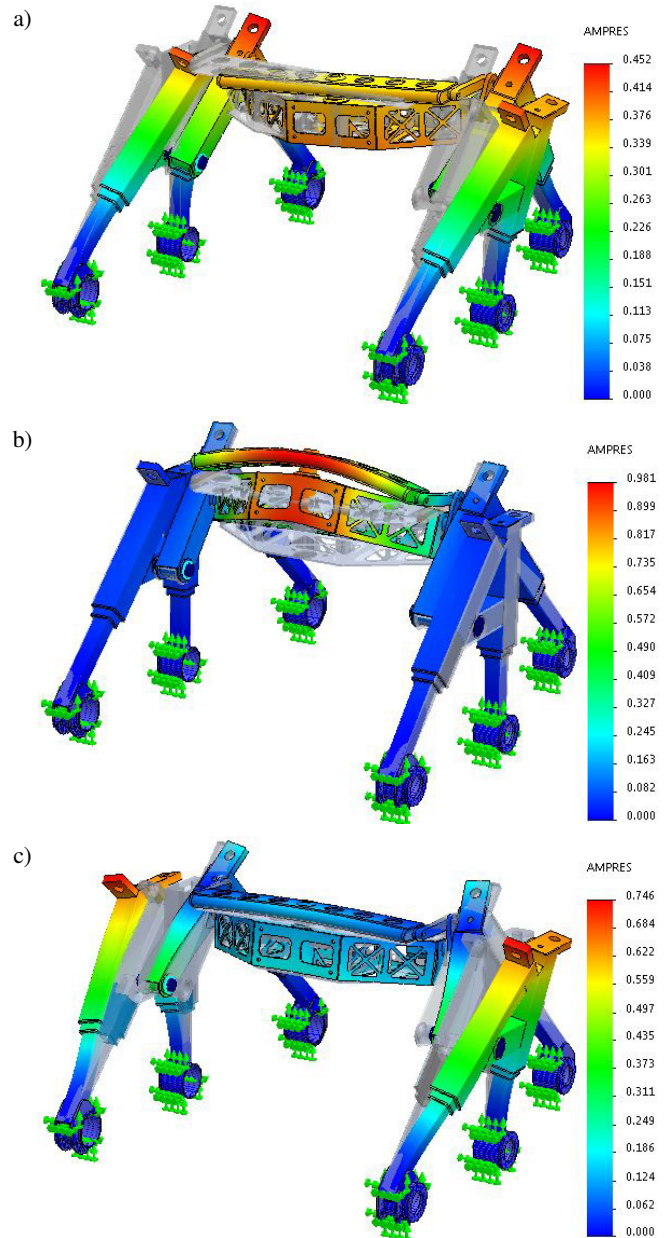
system used to change suspension length can also be damaged at great displacements. Lowering the suspension to the half of total length or lower shows that the first and second vibration modes are very similar to the previously discussed. However, the third vibration mode plotted in Fig. 10c and Fig. 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. The addition of small stiffening elements that should reduce the possibility of crack appearance should be considered. As presented, the change in length of suspension members greatly affects the vibration modes, resulting in the change of the most loaded elements. As mentioned before, the length of suspension members changes their slenderness factor. The longer the element, the lower slenderness while
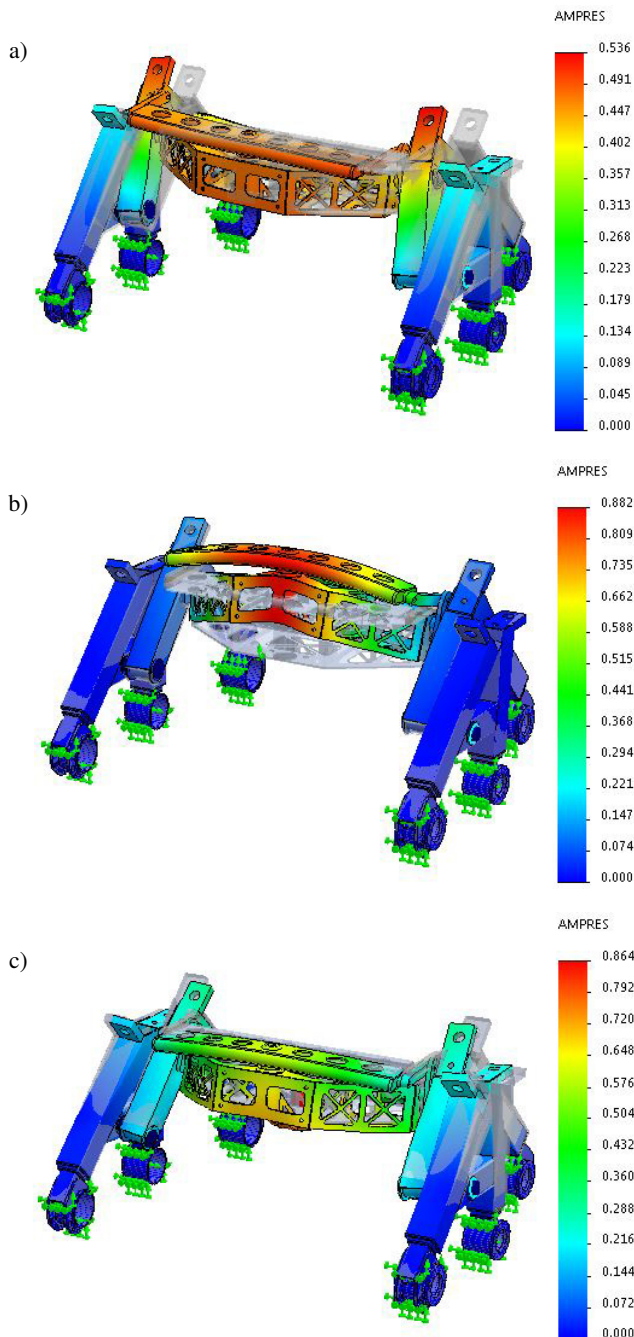
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a)

b)

c)

Fig. 11. Vibration modes – a construction made of aluminum with a minimum length of suspension; mode 1 – a), mode 2 – b), mode 3 – c)

Fig. 12. Vibration modes chart – a construction made from aluminum

Fig. 13. Vibration modes chart – a construction made from steel

Fig. 14. Vibration modes chart – a construction made from titanium

at the same time lower durability and higher total displacements and reduction in the frequency of vibrations. In the graphs below (Figs. 12–14) one has plotted the relationship between the length of suspension members and vibration frequency.

The vibration frequency magnitude is being reduced along with an increase in the length of the suspension member. This change is similar to 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 mentioning that a small in-
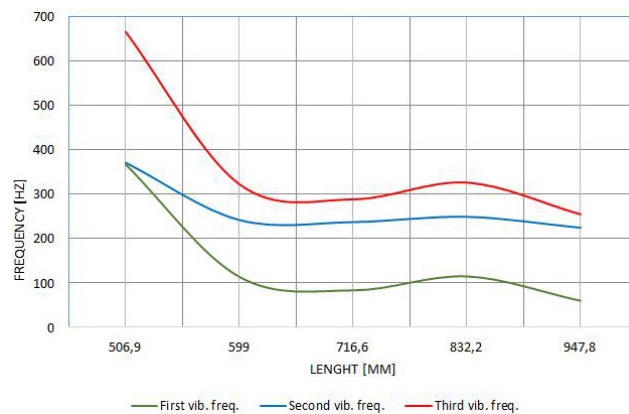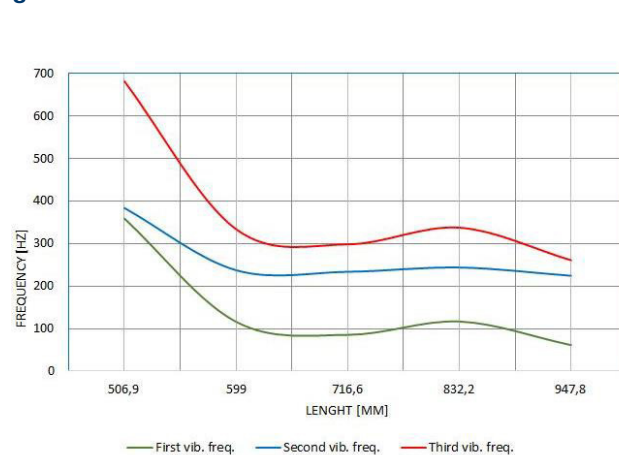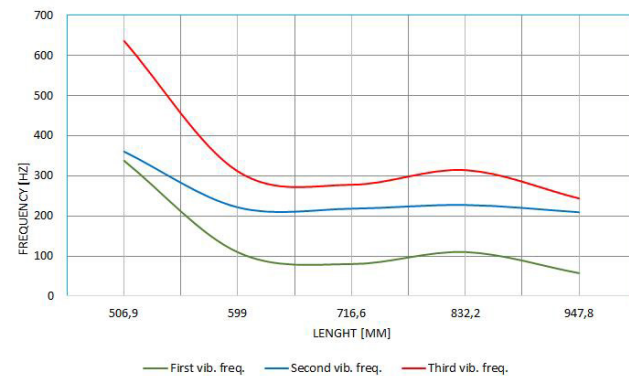
crease/reduction in vibration frequency can be observed with a further increase in the length of members. Above 830 mm, the vibration frequency has the lowest magnitudes. When the second vibration frequency is observed, it can be concluded that the most rapid reduction in vibration frequency is observed between 506–610 mm. Length above 610 mm has the smallest influence on vibration frequency from all studied curves. When the third vibration frequency is concerned, one can summarise that suspension length's influence on vibration frequency has the same tendency as the first one but at a greater ablative value.

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The first highest and lowest vibration frequency differences are as follows: aluminum – 307.27 Hz, steel – 297.33 Hz, titanium – 280.13 Hz. A similar order of materials (highest – lowest frequency) can be found for second and third vibration frequencies.

5. CONCLUSIONS

This paper discusses the influence of material properties on the vibration frequency of an active rocker-bogie suspension. The materials such as aluminum, steel and titanium grade 1 have been considered. It can be concluded that the most suitable material is aluminum due to the 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 introducing more durable elements like a differential bar, which can be changed to one made of carbon fibre material that will save a few grams or redesigning electric engines installation places. Titanium offers a good operating range at a much greater cost and can be a good option if aluminum construction fails during terrain tests. An interesting option in future simulation plans is a hybrid construction made of titanium and aluminum. The steel is not worth consideration due to the lowest vibration range, which 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 to test the influence of material properties on construction durability and vibration frequency at different lengths of each of the suspension members, which will simulate motion on sloped terrains like driveways, ditches, or raps. Also, a change in profiles type from rectangular into cylindrical should be discussed to find the optimum solution.

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