DESIGN AND STRUCTURAL ANALYSIS OF NEW MOWER DESIGN CAPABLE OF WORKING IN AREAS WITH 45° SLOPE

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Abstract. Areas with a large angle of inclination are usually difficult to access spaces with varied terrain. Increasingly often, they are recreational areas, meadows, or road lanes. Gentle slopes on the road lane and slopes of grass-sown viaducts are most often designed with an inclination angle of up to 45°. To mow these green areas, an agricultural tractor aggregated with a boom flail mower is usually used. The reach of the boom is limited; therefore, it was decided to develop a new mower design that has a greater reach than the boom of the flail mower and is capable of mowing areas with a slope of up to 45°. The aim of the work was to develop a conceptual design of a new mower capable of working in areas with a slope of 45° and a strength analysis of the main frame. The conceptual design included an analysis of available solutions, development of a 3D CAD model of the new mower, and a detailed strength analysis of the main frame of the new mower structure using the finite element method (FEM). The mower model and the analysis of the stability of the structure were performed in the SOLIDWORKS program, while the FEM strength analysis was performed in the ANSYS program. The designed frame model did not have nodes in which the stresses would be greater than 56% of the allowable stress in the material structure and 76% of the maximum allowable stress in the weld structure. The new mower structure for work in areas with a 45° slope meets all the assumed functions and has a great chance of industrial application.

Keywords: mower, slope of 45°, stability analysis, FEM, reduced stresses.

1. Introduction

We are increasingly trying to develop hard-to-reach areas with varied terrain, including those with a large slope. These areas are often adapted as recreational areas, meadows, or road lanes. Gentle slopes on the road lane and grassy slopes of grass-sown viaducts are most often designed with an angle of inclination of up to 45°. Road safety and aesthetics require cutting grass and other vegetation. An agricultural tractor aggregated with a flail mower is usually used to mow these green areas. However, the reach of the boom is limited, so it was decided to develop a new design of the mower, which has a greater reach than the boom of the flail mower and can mow areas with an inclination of up to 45°. When planning the design of a mower designed for areas inclined at an angle of 45º, many challenges arise. It should be noted that traditional single-axle mowers are susceptible to sloping on steep slopes, with a recommended maximum slope of up to 15° [1]. Zero-turn mowers can be particularly dangerous due to the risk of tipping over, especially when working on slopes [2]. An alternative may be modified two-wheeled tractors with a mowing attachment, which can successfully overcome slopes of 45 º and even steeper angles of up to 57 º. The modification allows the operator to maintain a standing position, increasing ease of use and safety [3]. Another solution may be autonomous mowers, especially those with all-wheel drive, which work exceptionally well on large slopes. These mowers do not show faults when mowing on steep slopes and, at the same time, provide excellent turf quality [4]. It is also worth noting that autonomous mowers equipped with an inexpensive satellite navigation system can maintain an accurate course on slopes of up to 25°, suggesting the potential for work on steeper slopes [5].

Finally, crawler mowers, designed with articulated suspension and adjustable blades. They can work on any slope, providing high-quality and economical mowing [6]. It is also worth pointing out the beneficial features of mowers for work on slopes, which include the following.

- Adjustable steering wheel: Provides better manoeuvrability and operator comfort on steep slopes [3].
- All-wheel drive: Provides stability and prevents failures on steep slopes [4].
- Track mechanism: Provides stability and efficiency, making it suitable for work on steep, muddy, and uneven terrain [6].
- Autonomous operation: Reduces labour input and increases safety by eliminating the need for an operator on dangerous slopes [4; 5].

The completed review of solutions allowed us to specify the purpose of the work as: development of a conceptual design of a new mower capable of working on areas with a 45° slope, along with a strength analysis of the main frame. The conceptual design included the development of a 3D CAD model of the new mower and a detailed strength analysis of the main frame using the finite element method (FEM), as well as stability analysis ensuring safety during operation.

2. Materials and methods

2.1. Strength analysis of the structure

For the developed concept of the main frame of the new mower structure made of open steel profiles and 5 mm thick bent sheet metal – connected by welds, to which the mowing head is attached, the most frequently used strength rules were applied, based on the hypothesis of the highest energy of shear deformation called the Huber-Misses_Hencky hypothesis [7]. It was planned that the main frame would be made of S235 steel (formerly St3S) to reduce the costs of prototype production. Then the first strength condition (1) was adopted:

$$k_{accept} \leq \frac{R_e}{x}, \tag{1}$$

where R_e – yield strength of the material (235 MPa);
x – arbitrary safety factor.

Based on the analysis of scientific literature [8; 9] and the experience of the research team performing the calculations, the following values of the safety factor were assumed:

- $x_{material}$ = 1.15 – for the material of construction;
- x_{welds} = 1.55 – for welds.

Hence, after rounding, we get the following values – k_{accept}:

$$k_{accept\_material} = 204 \text{ MPa};$$

$$k_{accept\_welds} = 152 \text{ Mpa}.$$

The 3D CAD model of the mower and analysis of the stability of the structure were performed in the SolidWorks 2024 program (Dassault Systèmes, Vélizy-Villacoublay, France), which had already been verified [9]. The discretization of the frame model and the strength analysis using the finite element method (FEM) were performed using the ANSYS 2024R1 program (MESco Sp. Z o. o. Bytom, Poland), which had previously been successfully used to analyze the maximum stress state of the loader frame [10]. During the construction of the computational model, an unstructured mesh was generated, which consists of tetrahedral elements and contains 983,136 nodes and 513,287 elements, while maintaining a high representation of the concept geometric form of the analyzed new mower frame structure. The size of the elements was selected to obtain an Aspect Ratio in the range of 1÷2 and to obtain the required density in places particularly exposed to stress. Then, for the purpose of strength analysis of the new mower frame design, the following boundary conditions were assumed: fixing the main frame at two points (pin connection), which was centrally supported by a hydraulic cylinder. The frame was loaded with a force of 500 N, which comes from the mass of the mowing-mulching head (2). The 3D CAD model of the new mower design for work in areas with a slope of 45 ° with a description of the individual elements is shown in Fig. 1 in the side view, and in Fig. 2 in the top view. The view of the new rendered photos of the designed mower design is shown in Fig. 3.

2.2. Stability analysis

Working in terrain with a high angle of inclination may cause a loss of longitudinal or transverse stability. Therefore, an important element of the calculations is to determine the coordinates of the center of gravity point, which affects the stability of the device while driving. In the case of the designed mower, the main goal was to create a structure with a low center of gravity, minimizing the probability of losing balance and tilting the device during operation. During stability analysis, the 45° angle of the device was reflected and the center of gravity was determined. The center of gravity was determined using the mass properties function (a function in Solid Works 2024), which allows the centre of gravity to be indicated, which is necessary for stability analysis.

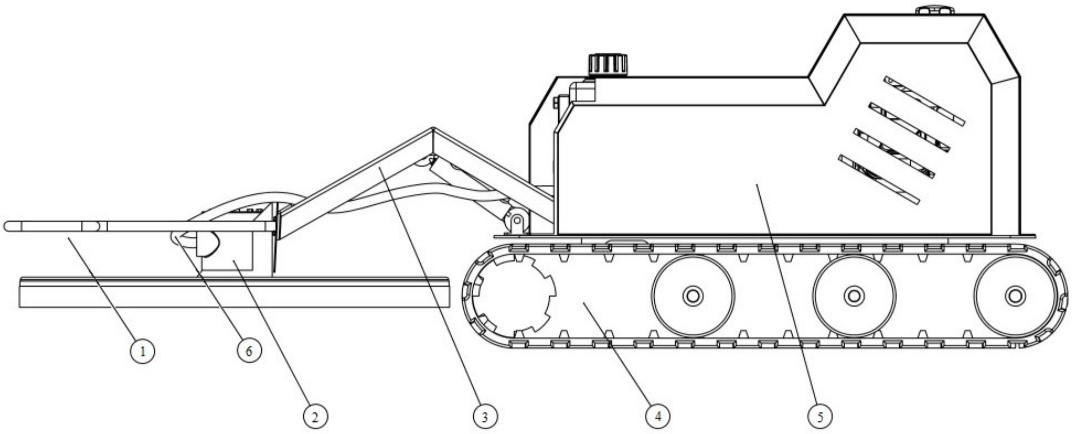

Fig. 1. **3D CAD model of the new mower design - side view:** 1 – protective barrier; 2 – mowing-mulching head; 3 – main frame; 4 – crawler chassis; 5 – cover; 6 – hydraulic hose

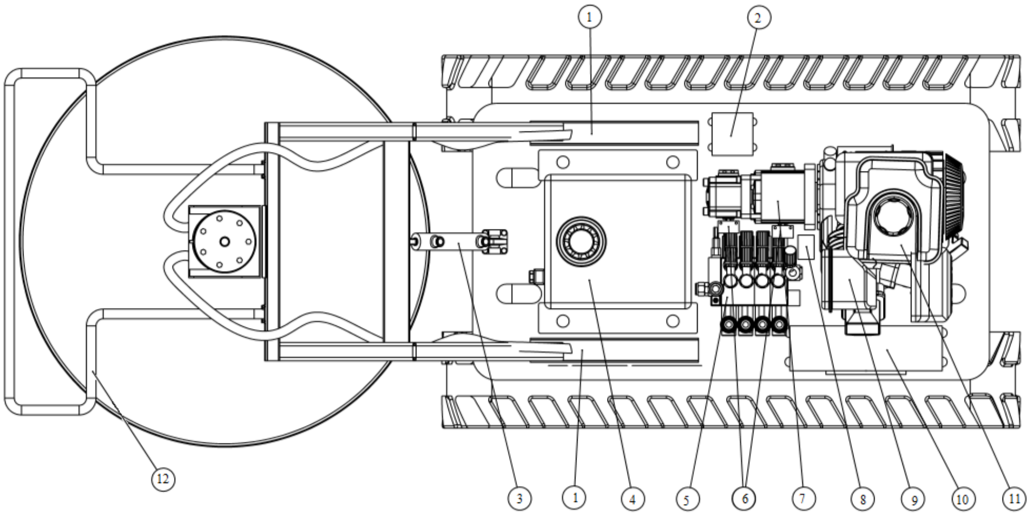

Fig. 2. **3D CAD model of the new mower design - top view:** 1– mounting bracket; 2 – remote controller; 3 – hydraulic cylinder; 4 – oil tank; 5 – hydraulic distributor; 6 – flow regulator; 7 – two-section pump; 8 – overflow valve; 9 – combustion engine; 10 – radiator; 11 – fuel tank; 12 – protective barrier

Fig. 3. **The view of the rendered photos of the designed new mower design**

3. Results and discussion

The results of the strength analysis and stability analysis of the new mower structure are presented in the following subsections.

3.1. Results of the strength analysis of the structure

The strength tests conducted focused on the analysis of the reduced Von Misses stresses and on the analysis of displacements for the concept developed of the main frame of the new mower. The first variant of the main frame (without reinforcement marked with a red arrow) did not meet the strength requirements, therefore a reinforcement in the form of a rib was developed. Figure 4 presents the results of the analysis of the reduced Von Misses stresses for the reinforced structure, which showed that the most stressed nodes occur at the bend of the profiles and amount to 115 MPa. Figure 5 presents the results of the displacement analysis, where the maximum displacements are 0.4 mm, which is very small compared to similar structures [11; 12] and at the same time acceptable. The assumptions adopted for this analysis were identical to those for the analysis of reduced stresses.

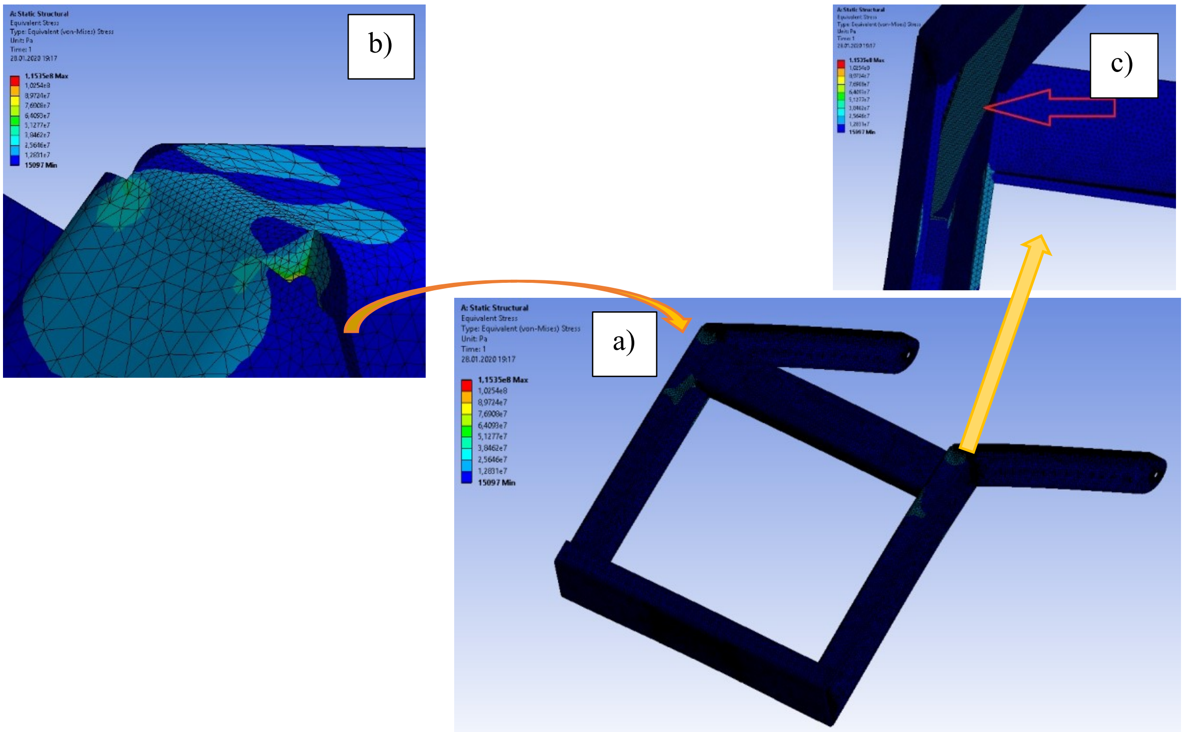

Fig. 4. **Stress analysis results after adding the rib:** a – reduced stresses for the entire model; b – reduced stresses in magnification - max stress 115, MPa; c – view of the developed reinforcement (rib)

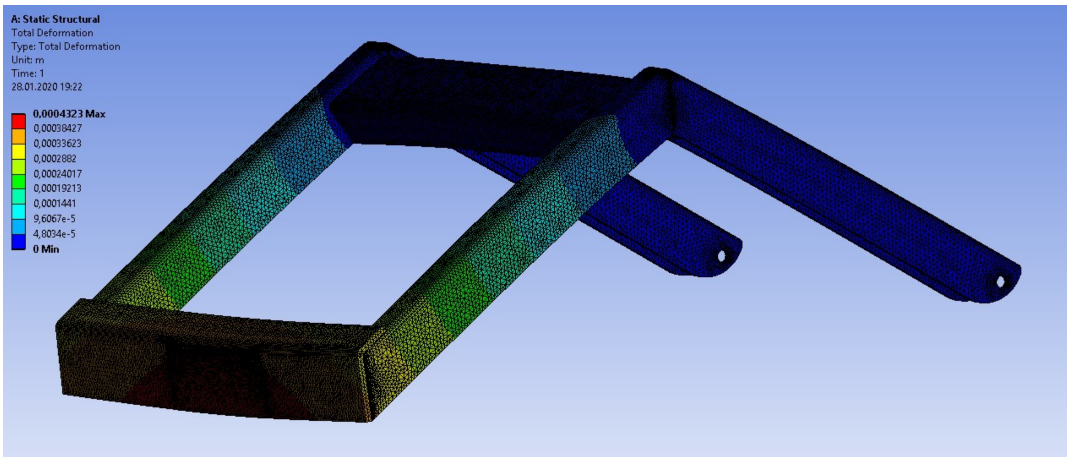

Fig. 5. **Displacement analysis results – the maximum displacement is 0.4 mm**

The presented research results and the method used are consistent with the results of the work of Marcinkiewicz et al. [13], who performed a strength analysis of the structural elements of the modular line, marking stress patterns for all the most important operating cases [13]. The indicated method (FEM) is often used for various analyses of mechanical structures [14-16], both in scientific works [17; 18] and in industry, to optimize load-bearing structures [19]. This method was also used by Chodurski et al. [20] to perform a strength analysis of the load-bearing structure of the head of an industrial robot, therefore, it should be considered that the FEM method is reliable.

3.2. Results of the analysis of stability of the structure

The analysis was performed for two variants: the first, when the mower works uphill (see Fig. 6a), and the second, when the mower works in a lateral slope (see Fig. 6b). In the presented Figure 6, in order to clearly present the determined center of gravity, a red line was drawn, which intersects the center of gravity, i.e. the point with vectors. A blue line was also drawn, which indicates the support point.

For the two variants of the operating mode presented, it is clearly visible that the center of gravity is shifted relative to the support point, which guarantees stability when working on slopes with a slope of 45º.

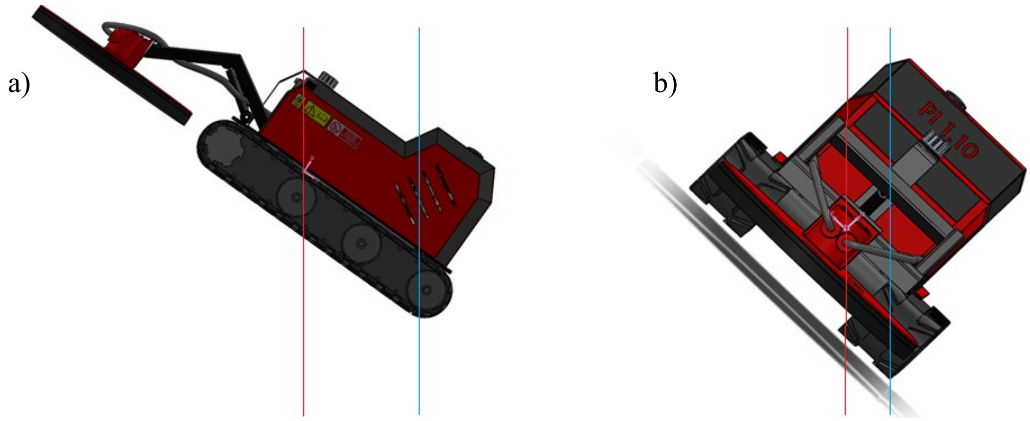

Fig. 6. **Stability analysis results of the new mower design:** a – when working uphill; b – when working on a side slope; red line – centre of gravity; blue line – support point

4. Conclusions

The strength analysis performed using the finite element method (FEM) shows that the new mower design, which can operate on terrain with a slope of 45°, meets all the assumed strength criteria. The 3D CAD model prepared and analyzed of the mower frame capable of working on slopes with an inclination of 45 ° did not have nodes in which the stresses would be greater than 56% of the allowable stress in the material structure and 76% of the maximum allowable stress in the welded structure. The designed structure of the main frame of the mower is also characterized by acceptable stiffness and is not susceptible to deformation in standard work and transport mode. Fulfilment of the assumed functions can also be confirmed by the stability analysis performed. The stability test results clearly indicate that the developed structure will prove useful during use on slopes with an inclination of 45°.

We planned the next step to conduct a strength analysis of the mower chassis frame and to develop a prototype of the new mower design to validate the test results obtained from the strength analysis. At this stage, we believe that the most suitable validation method will be the strain gauge method. In conclusion, the new mower design designed for a 45° slope meets all the intended functions and can be the basis for further research and modifications aimed at improving performance and reliability.

Author contributions

Conceptualization, Ł.G.; methodology, Ł.G.; software, Ł.G.; validation, Ł.G.; formal analysis, Ł.G and M.Z.; investigation, Ł.G. and P.W.; data curation, Ł.G. and P.W; writing – original draft preparation, Ł.G.; writing – review and editing, Ł.G and M.Z.; visualization, Ł.G. and P.W; project administration, Ł.G.; funding acquisition, Ł.G. All authors have read and agreed to the published version of the manuscript.

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