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Mobile Chipper Design with FEM System Application

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Advanced possibilities of using the finite element method (FEM) in the process of designing a mobile chipper were presented. The usefulness of vibration analysis with FEM in assessing the stability of a structure subjected to forces of variable and undetermined frequency was demonstrated. Based on hybrid analytical and numerical calculations, a , the proper accuracy of the calculations was shown and justification of using FEM to calculate the structure loaded with periodically changing forces was confirmed. Advanced possibilities of using the finite element method (FEM) in the process of designing a mobile chipper were presented. The usefulness of the FEM analysis of vibrations in assessing the stability of a structure subjected to variable and unsteady frequency excitation was demonstrated. On the basis of the hybrid calculations - analytical and numerical, the proper accuracy of the calculations was demonstrated and the purposefulness of using the FEM method for the calculations of the structure loaded with periodically changing forces was confirmed.

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1. Introduction

National forest management that supplies the domestic and export markets with wood raw material as well as private households, including wooded land and green land unsuited for cultivation, generates the need to process forest waste after agrotechnical operations [1]. Wood is obtained not only from planned production processes, the transformation of land but also as a consequence of restoring the usability of neglected areas or in order to remove damage resulting from weather phenomena.

Wood waste in the form of branches, trunks, roots, and limbs, as well as wood chips constitute a significant problem occurring after obtaining noble materials, which is the basis for further processing, forces the entity carrying out the operations to choose a relevant waste management method. The most widely used is the method of processing wood waste, mainly branches and small limbs, into wood chips that are used as calorific material or bedding and compost material by means of mechanical devices such as wood chippers or shredders.

Professional forestry production requires high-capacity equipment. Such machines of a considerable size are manufactured as elements coupled with an agricultural tractor that ensures mobility and transfers the drive with a PTO, machines powered by an

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motor with a compression ignition on a wheeled chassis, operating autonomously or in tandem with an additional vehicle and special vehicles that meet both the transport and utility function on both wheeled and crawler chassis [2, 3].

The main issue regarding the undertaken works is the reported fact of a deficit of small shredding machines that ensure high mobility on the site, with their own traction drive, for the operation of which one man is needed and does not depend on the presence of an auxiliary machine such as an agricultural tractor. The main problem implying the work undertaken is the noticed regularity of the existence of a deficit of small shredding machines on the market, ensuring high mobility in the field, having their own traction drive, for which one man is needed, not dependent on the presence of an auxiliary machine such as a farm tractor.

The basic problem is to design a structure of adequate strength, with both an optimum weight so that loads which are difficult to be determined resulting from the operation of the wood chipper are properly taken into account.

The objective of the paper is to demonstrate the possibility of using FEM systems in the strength testing of structural systems operating in states of undetermined dynamic mechanical loads.

2. Methodology of work

The application of FEM enables proper strength optimization of the structure, assuming that the loading forces are known. In the case of dynamic operations of the wood chipper, determining the forces and estimating their periodical nature constitute a significant problem. The applied method of simulating the resonance phenomenon of the frame assembly enables complete strength calculations of the load-carrying system. The applied FEM method (finite element method) allows for proper strength optimization of the structure, assuming that the forces forcing the loads are known. In the case of the dynamic operation of a chipper, a significant problem is to determine the extortions and estimate their periodicity. The applied method of simulating the occurrence of the frame assembly resonance phenomenon allows for full strength calculations of the superstructure.

Depending on the intended use of the wood yield obtained from the full-value raw material as well as wood post-production waste, a final product in the form of wood chips of varied dimensions or sawdust is obtained [4, 5]. The qualitative classification of wood chips is presented in the Polish standard PN-91/D-95009.

The production of cellulose and wood pulp that takes place in the appropriate enterprises tis carried out using technological lines where the main elements are a wood chipper producing primary processed wood chips, a sorting device separating the material necessary to further production, taking into account the desired fraction from impurities and a shredder which secondary coarse fractions and knots are processed [6]. The yield is transported to silos located under the machines, through pipes that suck out the yield from the shredding chambers and by means of belt conveyors. It should be mentioned that the energy industry has found a beneficial application for energy willow wood chips, which have a high calorific value that translates into economic results [7].

3. Initial assumptions

It was assumed that the analysed mobile wood chipper would be intended for shredding wood branches of any type of trees that are typical for the Central European climate and other wood waste with a diameter of up to 150 mm. Wood with high moisture typical for directly harvested raw material was taken into account. The operating conditions of the machine were considered as off-road conditions and a low-tech machine operation was assumed, allowing temporary overloads of the machine and the feeding of oversized raw material.

The shredding capacity was assumed to be 20 m^3/h. It was assumed that the possibility of shredding solid wood rollers with a diameter up to 150 mm should be ensured. Raw soft wood was adopted as the processed material. In further calculations, physical parameters corresponding to the type of birch wood were applied. The machine was designed mainly for cleaning works at a forest site carried out by one operator without the constant presence of an accompanying device such as a farm tractor. It was assumed that the structure must be able to be transported on site and on public roads using a three-point hitch of a farm tractor or the towing hook of a passenger car and its own drive over short distances, mainly serving technological vehicles on site.

The type of shredding mechanism that was assumed was a disc one, with a four-knife shredding mechanism and with discharge of the yield at the top. The discharge of wood chips was designed so that the material can be discharged to a height greater than the standard height of agricultural trailers. Regulation of the distance of wood chip discharge from the discharge chute was provided for by an adjustable flap. In the present version, no mechanism supporting the supply of wood material to the shredding chamber was included.

The designed machine is mounted on a frame made as a welded articulated structure made of hot-rolled steel profiles and metal sheets subjected to plastic processing. An electric drive axle with a DC motor supplied with energy accumulated in a battery was adopted to drive the rigid front axle while maintaining torsion of the front wheels. It is a solution that enables precise manoeuvring of the machine when the combustion engine is turned off. The rotational speed of the motor of the electric drive axle is regulated with a lever placed on the steering bar on the side of the swivel wheels of the machine. Road lighting was adopted for the 12 V installation as a standard that enables coupling with a vehicle and farm tractor was provided for.

The housing and safety covers were designed pursuant to PN-EN ISO 12100 [8, 9, 10] and PN-EN 1352 [11].

The body of the cutting unit was designed as a steel sheet structure welded with an openable top cover. The direction of movement and the turning of the wheels are carried out with a folding steering bar.

4. Results

For calculation purposes, Autodesk Inventor Professional 2023 software with a built-in material library was used [12]. The CAD/CAE environment is a product of Autodesk and belongs to the group of mid-range software. The capabilities and application of the software position Inventor below the NX system by Siemens. Due to price competitiveness and extensive support for academic centres, Inventor software is particularly popular in medium-sized design centers and production establishments. The software provides sufficient structural modelling and analysis options, as demonstrated in this study.

Simulations of design cases was conducted for non-alloy steel with the properties presented in Table 1. Simulations of design cases were carried out for unalloyed steel with properties presented in table 1.

Table 1. Material properties

Item	Name	Symbol	Value
1	Yield strength	R_e	250 MPa
3	Shear strength	R_m	300 MPa
4	Young' modulus	E	210 GPa

Source: Author's own work

4.1 Case 1 – checking static strength of frame

Frame unit RM01_2200_00_00 was subjected to analysis with regard to static strength taking into account the loads presented in Table 2.

Loads were applied in the form of point forces as:

- Weight applied after 50% value to two supporting nodes of the cutting unit
- Weight applied after 50% value to two supports of the motor
- Weight applied in the centre of gravity
- Weight applied after 25% value to four support points of wheels in the form of a reaction.

A triangular mesh with an average finite element size of 0.08 was adopted for the study. The simulation was performed for the number of nodes equal to 403365 and the number of finite elements amounting to 203528.

Table 2. Static loads

Item	Name	Symbol	Value
1	Weight of cutting unit with large gear box wheel	Q_{ZT1}	1442 N
3	Motor weight	Q_{S1}	589 N
4	Total weight of frame with roll bar	Q_{R1}	402 N
5	Total weight of frame, roll bar and drawbar	Q_{R11}	475 N

Source: Author's own work

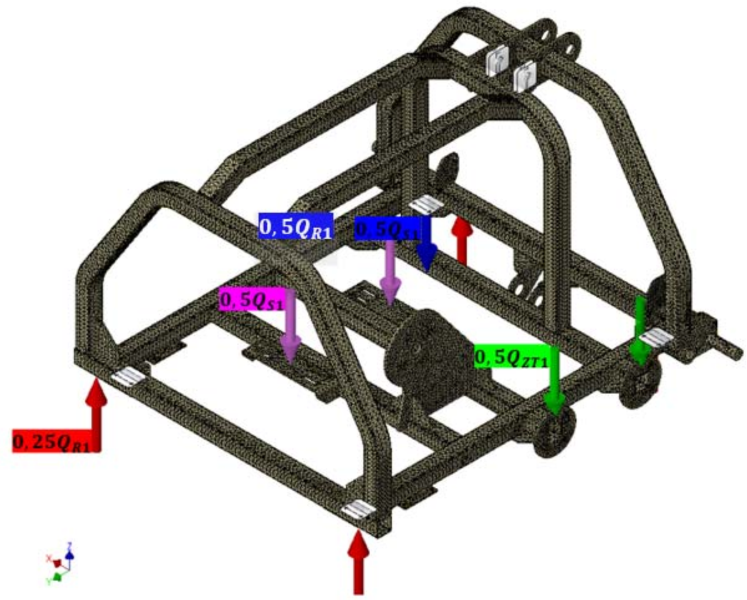

Fig. 1. Discrete model RM01_2200_00_00 with visible load and places of constraints
Source: Author's own work

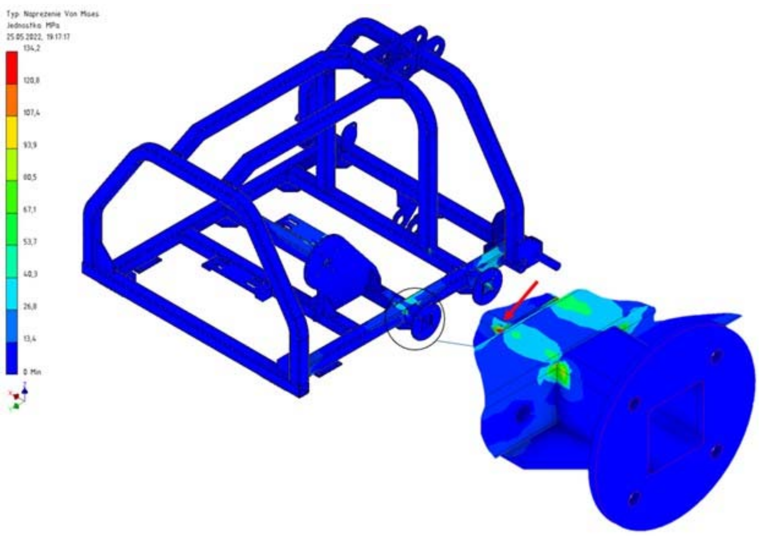

Fig. 2. Distribution of reduced stresses with visible peculiarity
Source: Author's own work

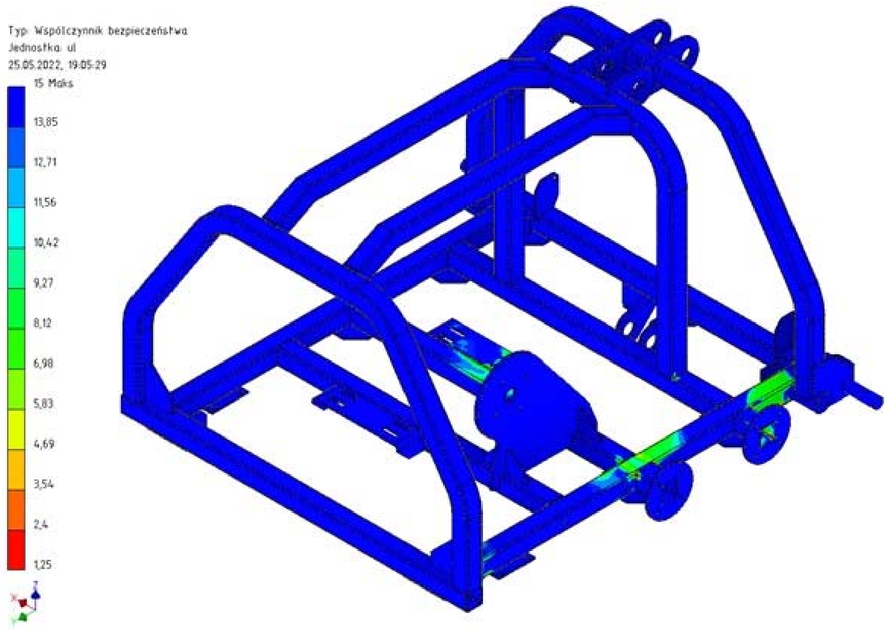

Fig. 3. Distribution of safety coefficient values
Source: Author's own work

The maximum value of stresses according to HMH 134.2 MPa was determined to be 134.2 MPa, which with the observed inaccuracy of the mesh in the place of joining the modelled shapes allows the frame to be considered as low-loaded. The lower value of the safety coefficient equal to 1.25 should be treated as a consequence of the emergence of a step increase in stresses caused by the inaccuracy of the mesh. Therefore, it should be considered that the safety coefficient of 2.4 is the lower limit [13,14].

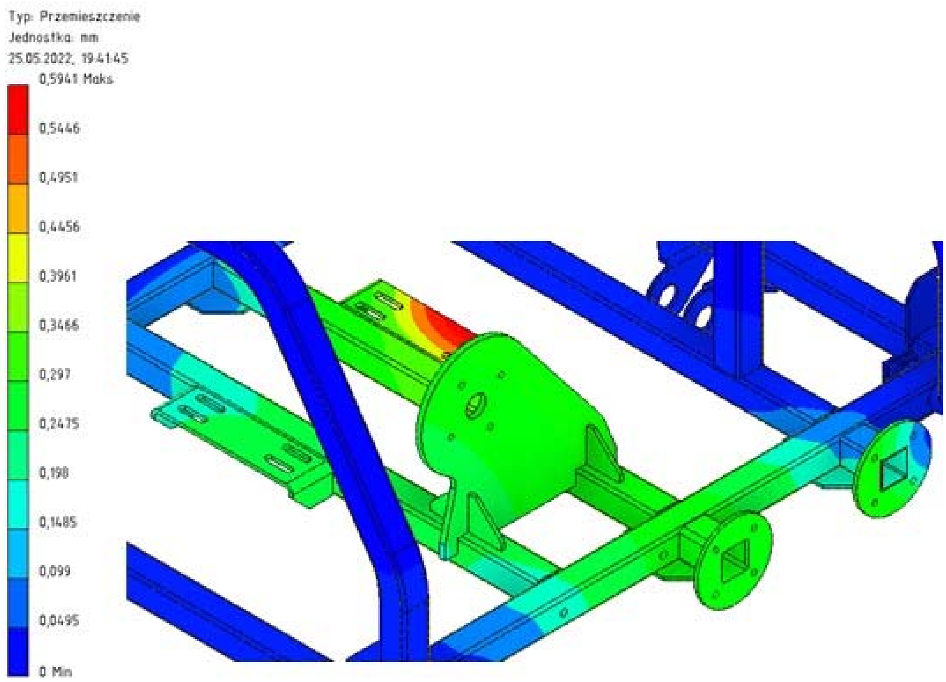

Fig. 4. View of distribution of determined displacements of structure points
Source: Author's own work

The excess stiffness of the structure shown in the simulation acts in favour of dynamic loads that may occur during operation, which are not analysed in this paper.

In the simulation, the geometry and weight of mobile frame RM001_2400_00_00 and geometry of cutting unit RM001_3000_00_00 were not included, except for their weight.

It was shown that the Inventor software environment is suitable for the strength analysis of the mobile chipper structure. The obtained distributions of the material strain confirms the correctness of the adopted structural solutions and the applied concepts of the load-bearing system.

4.2 Case II - simulation of occurrence of resonance phenomenon of frame unit

The cutting unit of the designed machine, due to the irregular nature of the work resulting mainly from the lack of dimensional repeatability of the cross-sections of the cut wood material, sparsely spaced cutting knives and variability of the cutting resistance with the presence of high values of cutting resistance forces implies the need to verify the supporting frame owing to the possibility of resonance vibrations.

When the frame of the mobile chipper is loaded with a cutting device whose frequency of natural vibrations coincides with the frequency of vibrations of the frame, an uncontrolled rise in the amplitude of displacements of the entire system may take place which may cause a failure. Therefore, to determine the initial conditions, the rotational speed of the cutting disc is changed from 500 rpm to 10 rps, then the obtained value is successively divided by the number of four cutting knives, which gives $f = 2.4$ Hz.

For the obtained frequency, the presence of resonance vibrations was checked initially using modal analysis. The idea of the simulation consisted in sending an impulse to the supporting structure of the frame and comparing the obtained value with the determined frequency. The frame model was immobilized in the places where the electric drive axle is mounted. For the obtained frequency, the presence of resonant vibrations was initially checked using modal analysis. The idea of the simulation consisted in sending an impulse to the supporting structure of the frame and comparing the obtained values with the determined frequency. The frame model was immobilized in the places where the electric driving bridge was installed.

For the purposes of the analysis, the number of modes was set to 5 and the frequency range of 2.4 Hz was chosen.

For the purposes of the analysis, the number of modes was set to 5 and frequency range was 2.4 Hz to 50.0 Hz was chosen. For the simulation, a triangle mesh was applied with an average finite element size of 0.08. The simulation was performed for the number of nodes equal to 404365 and the number of finite elements of 203528.

Fig. 5. Discrete model with visible nodes
Source: Authors own work

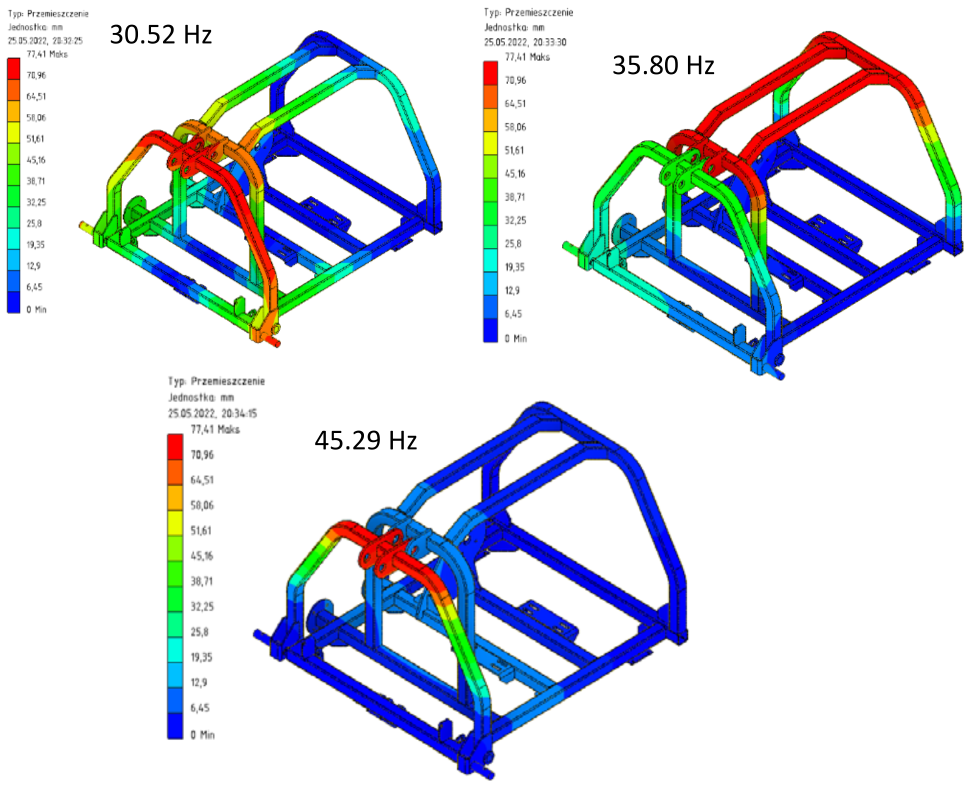

Fig. 6. Distribution of displacements for obtained form of vibrations
Source: Author's own work

Table 3 presents the obtained values of frequency.

Table 3. Summary of modal analysis results

Item	Item	Value
1	F1	1442 N
3	F2	589 N
4	F4	545 N

Source: Author's own work

Based on the obtained results, resistance of the structure to the occurrence of resonance vibrations during operation of the cutting unit was confirmed.

5. Conclusions

The problem of determining the wood cutting resistance in machines such as a chipper is a complicated issue, and often impossible to theoretically determine without the support of an empirical experiment. Thus, verification of the possibility of applying numerical calculations that replace empirical strength tests is desired. The developed design of the chipper was subjected to conventional calculations and numerical ones, the objective of which was to verify the correctness of the strength calculations of the structures subjected to variable loads of a determined frequency.

It was proved that FEM enables precise static strength calculations. The objective of the study was achieved since FEM enables verification of the degree to which dynamic and resonant loads influence the structural systems.

Based on hybrid calculations – analytical and numerical – the proper accuracy of calculations was demonstrated and the purposefulness of using FEM for calculating of the structure loaded with periodically variable forces was confirmed.

The use of software that enables simulations based on the finite element method enables initial estimation whether the adopted assumptions are consistent with the required strength conditions. An additional value of using FEM the time savings that the constructor would devote to physical confirmation of a sufficient strength overhead of individual parts and subassemblies, which considerably accelerates the development of the developed concept.

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