STRUCTURAL AND FATIGUE ANALYSIS OF EQUIPMENT FOR CUTTING WEEDS BETWEEN PLANTS ON THE SAME ROW

Gabriel-Valentin GHEORGHE[1], Gheorghe VOICU [2], Cătălin PERSU[3], Iuliana GĂGEANU[4],

In the technical literature, there are few studies on the structural and fatigue analysis of equipment for cutting weeds between plants on the same row. This paper presents the structural and fatigue analysis for such an experimental model equipment using experimental determined forces acting on the working bodies as inputs. The purpose of the study was to obtain the reactions from equipment's structure, equivalent stress, displacement, equivalent deformation, safety factor and calculation of equipment fatigue in order to optimize the equipment's design. The obtained results stress showed very high stresses within the equipment's working bodies and structure, above 600 MPa Von Misses stress, which will lead to structural failure if unresolved. In conclusion were proposed some structural changes in order to reinforce the resistance structure.

Keywords: weed control, FEM analysis, fatigue, damage

1. Introduction

Most of the research regarding structural and fatigue analysis on agricultural machinery was performed on equipment such as subsoiler / chisel, in theoretically / laboratory / field conditions.

In [2] the authors performed an accelerated test within laboratory conditions, based on previously recorded data during field tests. The loads specter was determined as mechanical strains which were recorded in discrete point on the resistance structure. The measuring points were chosen based of finite elements analysis – FEM, performed for the machine's structural model.

Tests performed directly in working conditions were the chosen method for assessing the qualitative indices of a deep soil loosening machine, the method for draft force measuring being based on strain gauge devices [3].

[1] Eng., National Institute of Research-Development for Machines and Installations Designed for Agriculture and Food Industry – INMA Bucharest, Romania, e-mail: gabrielvalentinghe@yahoo.com
[2] Prof., Biotechnical Systems Department, University POLITEHNICA of Bucharest, Romania, e-mail: ghvoicu_2005@yahoo.com
[2] Eng., National Institute of Research-Development for Machines and Installations Designed for Agriculture and Food Industry – INMA Bucharest, Romania, e-mail: persucatalin@yahoo.com
[4] Ph.D. Eng., National Institute of Research-Development for Machines and Installations Designed for Agriculture and Food Industry – INMA Bucharest, Romania, e-mail: iulia.gageanu@gmail.com

Other researchers performed tests within field conditions in order to improve the equipment's functioning [5], then studied the kinematics of soil loosening equipment and performed structural analysis on its structure [6] in order to assess the equipment's performances. In [4], the frequencies appearing in the structure were investigated using accelerometers, in order to determine their effect on the driver lifetime.

The finite element method is very commonly used in design stages of agricultural equipment, because it allows simulation of working processes [7-10], stress distribution in the structure [11; 12], assemblies, subassemblies or equipment [13], which are then verified by simulated and accelerated tests [14]. These simulations are also used in other industries [15], then to be validated in real conditions.

The finite element method is very common in design because it allows the simulation of processes [1, 2, 5, 6], the distribution of strain and stresses [3, 4], assemblies, subassemblies or equipment [7], which are then verified by testing in simulated and accelerated mode [8], in order to be validated in real conditions.

A similar innovative equipment intra-row weeder for vegetable crops was developed and fitted with rotating tine weeding mechanism [18]. Simulations were performed using mathematical models which were latter validated within working conditions.

Within this paper the following objectives will be achieved:

- static analysis evaluation in order to determine critical points.
- Installation of strain gauges on the critical points location in order to measure the maximum forces appearing in the structure.
- Performing structural and modal analysis in order to determine the maximum stresses in the structure.
- Interpreting the results and offering solutions in order to solve the problems appeared in the structure.

2. Material and method

Finite element analysis involves three distinct stages: 1) pre-processing, 2) processing and 3) post-processing of data. Pre-processing involves building a mathematical model of the element to be analyzed. The next step in FEM analysis is to solve the mathematical model created. It contains a system with a very large number of mathematical equations that will be solved by a module of the analysis program. Post-processing is that section of the analysis that involves the analysis and interpretation of the results obtained. [1]

The equipment for cutting weeds between plants experimental model used for experiments within this paper is composed of a frame on which are mounted two classic hoeing sections each equipped with two working bodies driven by electric actuators, two-wheel driving and adjusting the working depth, two supports for the cameras and intelligent control system.

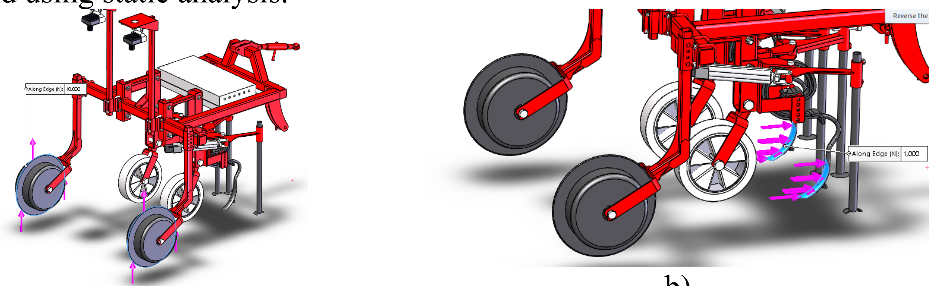
The structure's optimization methodology used consisted of the following stages:

- Determination of critical points on the structure and working bodies through statical analysis, estimating reaction forces;
- Application on strain gages, strain calibration in order to measure actual forces, experimentation within field conditions with force recording, data processing and interpretation;
- Statical and fatigue analysis calibrated with input data from real experimentation;
- Structure optimization through analysis results for various structural changes.

In the first stage of this study, the simplified 3D geometric model of the equipment for cutting weeds between plants (fig.1) on the same row was made. The static analysis was performed on the whole equipment for cutting weeds between plants on same row, in order to calculate its critical points. Further on, the fatigue analysis was performed for estimating after how many cycles of operation, material fatigue appears.

Fig. 1. Equipment for cutting weeds between plants

The real forces acting on the working bodies (Figure 2) were measured in the field, in working conditions, using strain gauges applied in the critical points identified using static analysis.



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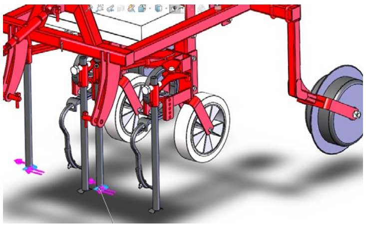

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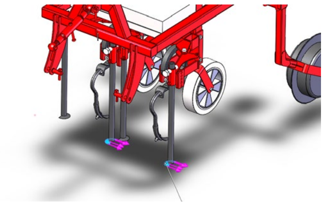


d)

Fig. 2. Forces acting on the working bodies during actual work

The positioning of the strain gauges (Figure 3.a) was performed after the introduction of exaggerated forces until the von Mises yield criterion reached a critical value, in order to reach the most vulnerable areas. After determining the positions of the strain gauges, they were glued on the structure according to figure 3.a., and in figure 3.b. the installation and positioning of the Quantum X system for data acquisition. The results for each strain gauge are exemplified in the following graphs (Figure 4). The measurements were performed for 3 different speeds and 3 working depths, commonly used during work.

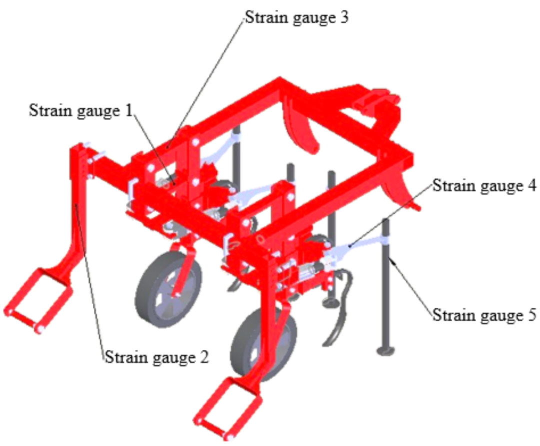
Input data for running simulations.

Defining the material, the forces acting on the structure, fixing the structure and discretizing the elements.

The material of the whole structure is S275JR, apart from the working bodies that interact with the soil, for these working bodies, the material is a harder steel, namely E355. The properties of the material are presented in Table 1.

a)

b)



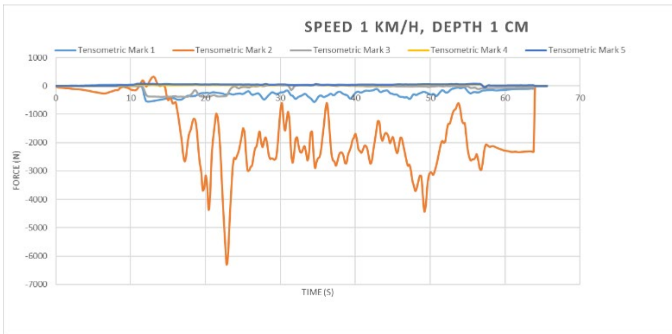
c)

Fig. 3. a) Gluing the strain gauges on the frame in order to perform field tests, b) Positioning and mounting the device for measuring specific deformation on the surface of metal structures – Quantum X, c) Positioning of strain gauges on equipment

Table 1

Properties of materials used in the analysis

Property \ Material	S275JR	E355
Elastic Modulus, N/m^2	2.100000031e+11	2.100000031e+11
Shear Modulus, -	7.9e+10	7.9e+10
Mass Density, kg/m^3	7800	7800
Tensile Strength, N/m^2	410000000	550000000
Yield Strength, N/m^2	275000000	275000000
Thermal Expansion Coefficient, 1/K	1.1e-05	1.1e-05
Thermal Conductivity, W/(m·K)	14	14
Specific Heat, J/(kg·K)	440	440



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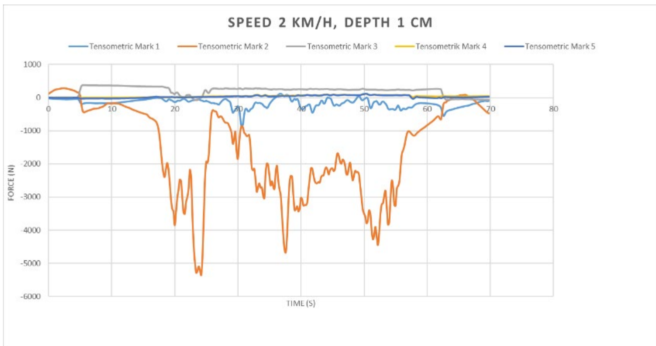

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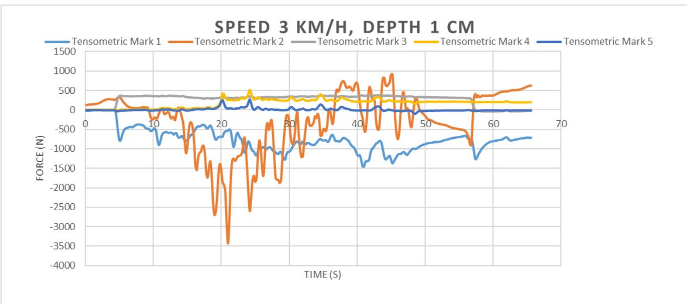

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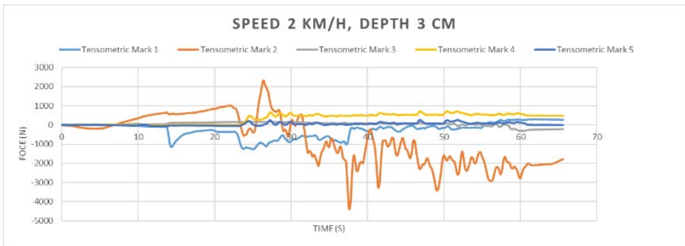

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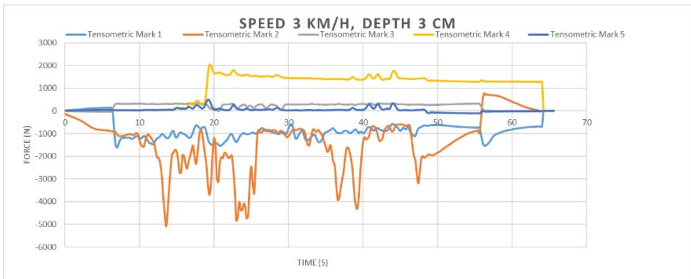


e)

Fig.4. Graphs of forces measured using strain gauges
a) speed 1 km/h, depth 1 cm, b) speed 2 km/h, depth 1 cm, c) speed 3 km/h, depth 1 cm,
d) speed 3 km/h, depth 3 cm, e) speed 3 km/h, depth 3 cm.

Table 2

Interpretation of graphs

Input data	Positioning of tensometric marks	Average value (N)
a) speed 1 km/h, depth 1 cm	Strain gauge 1	259.9
	Strain gauge 2	1826.5
	Strain gauge 3	78.6
	Strain gauge 4	32.3
	Strain gauge 5	43.8
b) speed 2 km/h, depth 1 cm	Strain gauge 1	161.8
	Strain gauge 2	2534.7
	Strain gauge 3	230.5
	Strain gauge 4	60.7
	Strain gauge 5	47.8
c) speed 3 km/h, depth 1 cm	Strain gauge 1	813.3
	Strain gauge 2	466.6
	Strain gauge 3	338.5
	Strain gauge 4	185.4
	Strain gauge 5	15.8
d) speed 3 km/h, depth 3 cm	Strain gauge 1	344.2
	Strain gauge 2	693.5
	Strain gauge 3	78.5
	Strain gauge 4	348.8
	Strain gauge 5	45.7
e) speed 3 km/h, depth 3 cm	Strain gauge 1	949.3
	Strain gauge 2	1533

	Strain gauge 3	248.1
	Strain gauge 4	1111.6
	Strain gauge 5	42.6

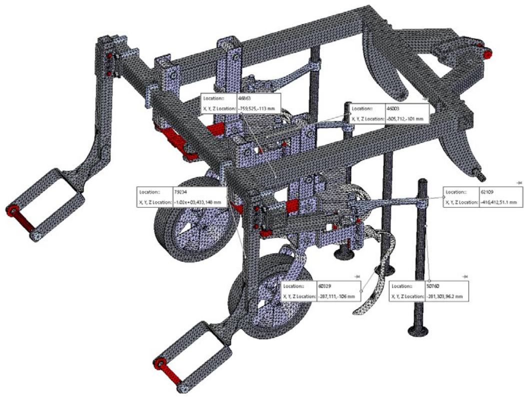


Fig.5. Positioning of the measurement points within the static analysis

The equipment was designed with SolidWorks software, it contains a number of 30 subassemblies, respectively 110 parts. After fixing the equipment in the three points (Figure 3) the calculated forces are applied and the meshing of the structure is made, resulting in a mesh consisting of 42168 knots and 125733 elements.

After entering the input data, the static simulation of the equipment was run. The results obtained are presented in figure 9, and the graph of the measured response in nodes is presented in Figure 6. The measurement was performed in the points where the strain gauges were positioned. A correlation of the gauges in Figure 3 with the points in Figure 5 would be the following.

Strain gauge 1 – point 46003, Strain gauge 2 – point 79234, Strain gauge 3 – point 46863, Strain gauge 4 – point 62109, Strain gauge 5 – point 50760

In this paper, the fatigue of the three-point hitch due to the raising and lowering of the equipment at each end of the row was calculated, the force introduced being the weight of the equipment - approximately 1400 N. In materials science, fatigue weakens a material caused by repeatedly applied loads. In addition to the calculation performed on the three-point coupling, a fatigue calculation was performed on the working bodies entering one by one between the plants and driven by the actuator. It was a progressive and localized structural damage that occurs when a material is subjected to a cyclic load.

The nominal values of the maximum stress causing such damage may be much lower than the strength of the material usually referred to as the final tensile stress limit or the flow stress limit. Fatigue occurs when a material is subjected to repeated loads and unloads. If the loads are above a certain threshold, microscopic cracks will begin to form at stress concentrators, such as the surface. [16]

First fatigue simulation was made based on calculation of the loading and unloading cycles performed by the equipment was performed as follows: due to the fact that the average length of the plots in Romania is about 500 m and the working width of the equipment is between 0.8 - 1.2 m, the studied crop for calculating the number of cycles being lettuce which needs 2-3 mechanical crop maintenance works per year, and the speed of the equipment is 1, 2 and 3 km/h, the number of cycles was computed using the following empirical formula:

$$\boldsymbol{n} = \frac{\boldsymbol{v}}{\boldsymbol{l}}\text{, cycles}\cdot\text{h}^{-1} \qquad (1)$$

where:

n – number of cycles, v –movement speed of the equipment (m/h), l – plot length (m)

The second calculation for fatigue was made for the working bodies entering one by one between the plants, being driven by the actuator. The input data in the case of this analysis are the same as in the static simulation performed in the first case, respectively results from this analysis. The maximum force registered on strain gauges 4 and 5 is 500 N, this being the maximum force acting on the active body of the equipment.

3. Results and discussions

The nonlinear response of material sustaining a prescribed thermo-mechanical process is in general related with the rearrangement of microstructures rendering the irreversible thermodynamic process. If the energy dissipation in relation with the thermodynamic process can be assumed as quasi-static one, the internal variable based irreversible thermodynamics. The numerical technique that was used to calculate the results is Newton-Raphson Technique. For each node on which was applied a strain gage, a simulation was done in static conditions using as excitation the corresponding measured forces within the field, simulated from zero to peak, and the results are presented in figure 6.

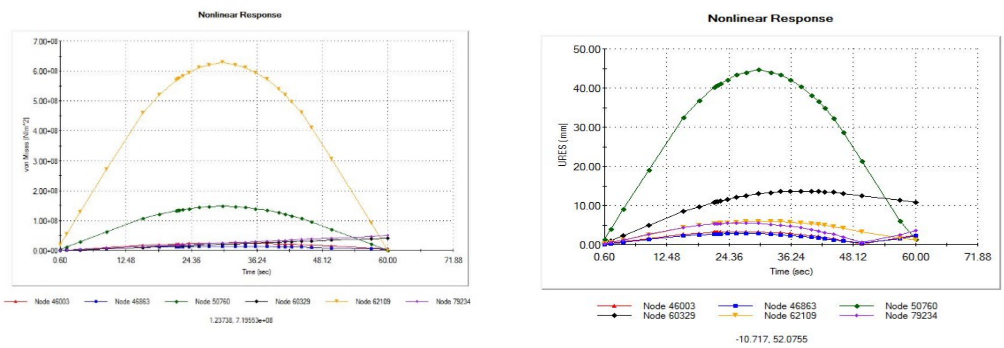
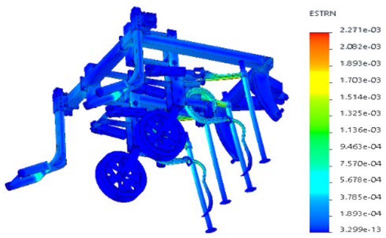


Fig.6. Variation of tensions and displacements in the points from fig.5.

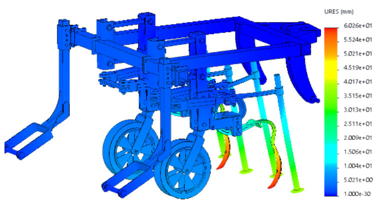
The variation of the simulated values in Figure 6 are supported by situation encountered during actuals tests, presented in Figure 7, where there can be seen very large displacements for the working bodies, due to the sub-dimensioning of the working body support. Due to the simulations and field tests, improvements will be made to the constructive solution.

Fig.7. Images from field tests.

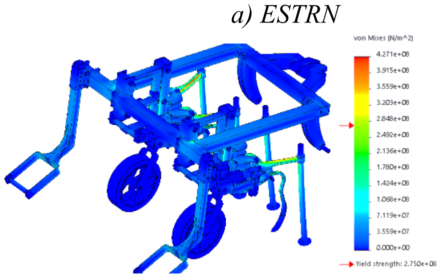
The main results of the static analysis are: the distribution of the vector field of the relative displacement, the distribution of the specific deformation fields and the Von Mises stress. Also, an important result of the analysis is the distribution of the safety factor. The distribution of the total values of specific deformation is graphically represented by the color map. Due to the fact that we work in the elastic domain, the maximum strain will be located in the same area with the maximum specific deformation. [17]



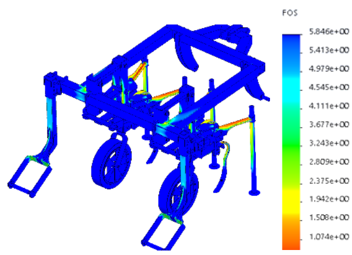
a) ESTRN



b) Displacement



c) Von mises stress



d) Safety factor

Fig.8. Results of static analysis

Due to the results of the static analysis, it is observed that when applying the forces calculated in the experiments performed in the field, the mounting plate of the active body will yield in time, the Von Mises value in that area reaching the maximum yield strength, therefore the structure will be optimized by increasing the thickness of the mounting plate or by adding reinforcements in that area in order to improve the structure.

In conclusion, for the 3 speeds of the equipment we have the following:

$1000\ m\cdot h^{-1} / 500\ m = 2\ cycles \cdot h^{-1}$

$2000\ m\cdot h^{-1} / 500\ m = 4\ cycles \cdot h^{-1}$

$3000\ m\cdot h^{-1} / 500\ m = 6\ cycles \cdot h^{-1}$

The working speed is chosen depending on the distance between the plants, namely the protection zone of the plant; if a high speed is chosen there is a risk of damaging the plants. According to Figure 9 it is observed that after approximately 5000 cycles (lifting the equipment at the end of the row) cracks begin to appear in the structure. Table 3 shows the life time of the equipment depending on the working speed for the plot length of 500 m.

Table 3

Speed ($m\cdot h^{-1}$)	Plot length (m)	Number of working hours	Life time (years)	Total number of cycles until cracks appear
1000	500	2500	15	5000
2000	500	1250	7,5	
3000	500	833	5	

The calculation based on speed is made because there is a short window to cut weeds, if you only have one week to destroy weeds in one mechanical maintenance cycle. The longer the plots, the later the cracks will appear.

Fig. 9 Results of the fatigue analysis of the equipment frame when lifting it at the end of the row

Due to the results obtained during the fatigue analysis, new reinforcement elements will be added in the area where the highest values were discovered, and after adding these reinforcements, the optimization analysis will be performed according to the fatigue calculation.

The fatigue analysis of the working bodies resulted in a number of 38000 cycles (Figure 10), meaning that the equipment will process and destroy the weeds between about 80000 plants, in the actual construction until the first degradation, namely a damage of only 2.5% according to Figure 11.

Fig.10. Results of the fatigue analysis of the bodies that enter on the row between plants.

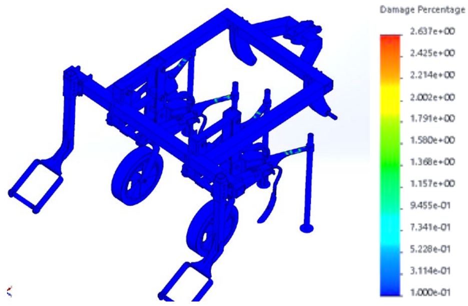


Fig.11. Damage percentage of about 2.5% after 38 000 cycles

4. Conclusions

Due to the presented methodology, it is possible to run later after performing the various solutions to improve the structure in order to offer the best structure.

The Von Mises stress diagram shows that the critical value of the material is reached, as well as the small number of cycles until the cracks resulting from the fatigue analysis of the working body driven between plants in turn by the electric actuator appear, therefore an optimization of the structure is obviously necessary in order to put the equipment into operation. This equipment is in the experimental model phase and will be improved in the future. The structure will be reinforced in order to reduce the high values obtained.

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