Krzysztof ZEMBROWSKI, Marek DANIELAK, Paweł STOBNICKI,
Aleksander RAKOWICZ, Sylwester WEYMANN
Industrial Institute of Agricultural Engineering
ul. Starołęcka 31, 60-963 Poznań, Poland
e-mail: office@pimr.poznan.pl

VIRTUAL MODELS OF A NEW VERSION OF A LOADING TRANSPORTER UNIT IN A TRACKED VEHICLE - KINETOSTATIC AND STRENGTH ANALYSIS

Summary

The article presents a new version of a modified loading transporter unit in a specialized tracked vehicle, made as part of the development project no. WND-POIG.01.03.01-00-164/09: "An integrated technology for the protection of wetlands against succession of vegetation causing a degradation of the natural environment" associated with the removal of unwanted vegetation from protected areas, particularly from National Parks and Natura 2000 areas. The design of a new loading transporter unit developed by the Department of Power Engineering and Dynamics of Agricultural Machines of PIMR in Poznań, was intended to improve the structural strength, as well as modify and simplify the previous design. A virtual model of the loading transporter unit was created, strength and kinetostatic analyses were performed with the use of SolidWorks 2014 software. In addition, the paper includes information on the original structural solution and presents a new, modified version of the loading transporter unit, adapted and tested in real-life field trials of the loading transporter unit of the tracked vehicle.
***Key words**: loading transporter unit**,** tracked vehicle, kinetostatic analysis, strength analysis*

MODELE WIRTUALNE NOWEJ WERSJI WYSIĘGNIKA ROBOCZEGO POJAZDU GĄSIENICOWEGO – ANALIZA KINETOSTATYCZNA I WYTRZYMAŁOŚCIOWA

Streszczenie

W artykule przedstawiono nową wersję zmodyfikowanego wysięgnika roboczego specjalizowanego pojazdu gąsienicowego, realizowaną w ramach projektu rozwojowego nr WND-POIG.01.03.01-00-164/09 pt.: „Zintegrowana technologia ochrony obszarów wodno-błotnych przed sukcesją roślinności powodującej degradację środowiska przyrodniczego" związanego z usuwaniem niepożądanej roślinności z chronionych terenów zwłaszcza parków narodowych, parków krajobrazowych oraz obszarów Natura 2000. Projekt nowego wysięgnika opracowany przez Zespół ds. Energetyki i Dynamiki Maszyn Rolniczych PIMR w Poznaniu miał za zadanie poprawę wytrzymałości konstrukcyjnej, zmodyfikowanie i uproszczenie poprzedniej jego konstrukcji. Wykonano model wirtualny wysięgnika roboczego, przeprowadzono analizę wytrzymałościową oraz kinetostatyczną przy użyciu oprogramowania SolidWorks 2014. Ponadto w artykule zawarto informacje dotyczące pierwotnego rozwiązania konstrukcyjnego i przedstawiono nową, zmodyfikowaną wersję wysięgnika, którą zaadaptowano i sprawdzono podczas rzeczywistych prób terenowych modułu roboczego pojazdu gąsienicowego.
***Słowa kluczowe**: wysięgnik roboczy, pojazd gąsienicowy, analiza kinetostatyczna, analiza wytrzymałościowa*

1. Introduction

The virtual model of a new version of the loading transporter unit of the tracked vehicle was developed as part of project no. WND-POIG.01.03.01-00-164/09 [1] pursued at the Industrial Institute of Agricultural Engineering (PIMR) in Poznań, by the Department of Power Engineering and Dynamics of Agricultural Machines. The key objective of the research project pursued at PIMR was to develop efficient and effective technologies serving the purpose of protective operations of mowing unwanted vegetation from wet and boggy areas of national and scenic parks as well as natural reserves, in order to restore natural breeding areas for rare and endangered species of birds, e.g. aquatic warblers [2, 3]. In order to achieve that purpose, PIMR designed and made, in collaboration with Hydromega [7] and Promar companies, a real model of a specialised Tracked Vehicles Unit (TVU). The key objective was to develop a light structure for a unit of tracked vehicles and tool modules, which would feature low impacts on the ground [4]. The tracked vehicle was equipped with, among other things, a front loading transporter unit of the working module [5] designed to be aggregated with various types of specialised tools for mowing, cutting and shredding biomass in protected areas. A change of working conditions for the loading transporter unit, associated with its integration with new and heavier working modules, necessitated a modification of its existing design. Virtual models were developed for the new version of the loading transporter unit of the tracked vehicle (TV), which will ensure a proper cooperation with new and heavier tool modules. The new models were subjected to kinetostatic and strength analyses with the use of the SolidWorks 2014 system [9].

2. The loading transporter unit - original version

The loading transporter unit in a specialized tracked vehicle is mounted in the front of the vehicle body. The key purpose of the loading transporter unit with a quick hitch [6] is to integrate the machine with the tool module, e.g. mower, mowed biomass reception unit and its further transport by the main conveyor of the tracked vehicle, whose outlet is positioned above the container in the transportation module (trailer). The loading transporter unit is also designed to enable a proper positioning of the coupled tool module in the working position against the ground. The following three pairs of hydraulic servomotors serve this purpose:

1. servos of the quick-coupling ensuring a correct tool tilt angle against the ground,
2. lateral servos providing the sliding of the loading transporter unit,
3. servos of the bearing frame lifting and lowering the loading transporter unit.

The structure of the original version of the loading transporter unit consists of a bearing frame made of two channel bars connected in their middle parts with rectangular shapes, and a quick hitch designed mainly to integrate the working modules (Fig. 1). The transportation system of the loading unit consists of a conveyor belt bound on two drums: a front, driven drum and rear, driving drum connected with a hydraulic motor, as well as guiding rolls and rollers supporting the belt. The belt is tightened up by a tension system of the loading transporter front drum.

Fig. 1. The tracked vehicle during sedge cutting trials - PIMR-BE archives

Rys. 1. Pojazd gąsienicowy podczas prób koszenia turzycy – archiwum PIMR-BE

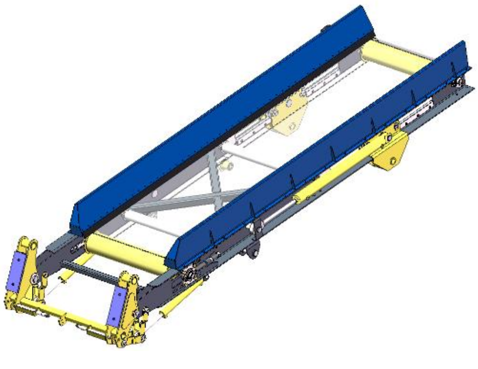


Fig. 2. The virtual model of the original version of the loading transporter unit - PIMR-BE archives

Rys. 2. Model wirtualny pierwotnej wersji wysięgnika roboczego – archiwum PIMR-BE

TVU field tests (Fig. 1, 3, 4) carried out during biomass mowing and collection trials, demonstrated a necessity for redesigning the original version of the loading transporter unit in order to improve its torsional strength.

In the process of mowing field trials carried out in a boggy and frequently uneven and heterogeneous land, it was found out that the loading transporter unit with a heavier grass mowing tool coupled with it, is exposed to substantial dynamic forces and an excessive torsion of the structure.

Field tests carried out under hard weather conditions (various kind of dust, occasional showers), revealed difficulties in controlling the movement of the tool module locking pins in the quick hitch of the loading transporter unit. Insufficient clearance on the locking pins in sand and dust conditions, as well as the applied mechanism control using flexible connectors, made it difficult to properly control the locking mechanism.

Fig. 3. The tracked vehicle during field tests - PIMR-BE archives

Rys. 3. Pojazd gąsienicowy podczas badań terenowych – archiwum PIMR-BE

Fig. 4. Shredder-transporter cooperation - PIMR-BE archives

Rys. 4. Współpraca rozdrabniacza z wysięgnikiem – archiwum PIMR-BE

During the field trials, an irregular work of the belt conveyor was observed, and the belt slipped sideways. Attempts to change the belt tension were unsuccessful, because the material was stretched excessively, and the one-sided tightening mechanism did not provide sufficient tension regulation.

The results of TVU field trials revealed a necessity to modify the structural components of the previous loading transporter unit or to design its new and improved version, showing greater torsional strength in particular. It was considered desirable to develop a new version of the loading transporter unit and quick hitch, bearing in mind the bigger weight of new tool modules (from 600 kg to approx. 720 kg) and a required increased range of tool dislocation against the ground, as well as to ensure the right depth of tool submersion under water.

3. The new version of the loading transporter unit

The design of the new version of loading transporter unit with a quick hitch should provide the following:
1. greater strength, torsional in particular,
2. increased adjustment range of the tool's hight during mowing operations used for soft, hard and aquatic vegetation,
3. preservation of a possibly similar weight of the loading transporter unit,

Fig. 5. The virtual model of the new version of the loading transporter unit - PIMR-BE archives
Rys. 5. Model wirtualny nowej wersji wysięgnika roboczego – archiwum PIMR-BE

In view of the above, it was decided to modify the design of the bearing frame, which allowed for the removal of adverse elastic sprain occurring in the original loading transporter unit. The frame was reinforced with the use of closed rectangular shapes measuring 60x40x3 mm. The side shapes of the beam were toughened, along the whole length, with the use of a channel bar which plays the role of a linear runner for the slide blocks of sliding runner beams (Fig. 5).

The rolling movement was replaced with sliding movement, which features greater stiffness, primarily due to a bigger area of force distribution on the runner sliding surfaces. To minimise clearance, the plates were tightened up on both sides of the runners. The sliding blocks were made of TECAFORM AD AF, i.e. a polyamide material featuring a relatively low friction coefficient $\mu = 0.2$ and increased abrasive wear resistance [8].

In order to achieve an easy locking of the aggregated tool modules with the quick hitch, guiding sleeves were fixed on both sides on the inner walls of the quick hitch, which ensured coaxial alignment of the locking pins and holes made in the sleeves, which thus extended their guidance (Fig. 6). In addition, the lock/unlock system of the locking pins was redesigned with the flexible connector mechanism being replaced with a lever mechanism controlled by a pneumatic servo.

Another task from the ergonomic perspective was to solve the issue of belt tension adjustment. To achieve this, it was decided to implement a two-sided belt tension adjustment system in the shapes of the bearing frame, in the top and bottom sections.

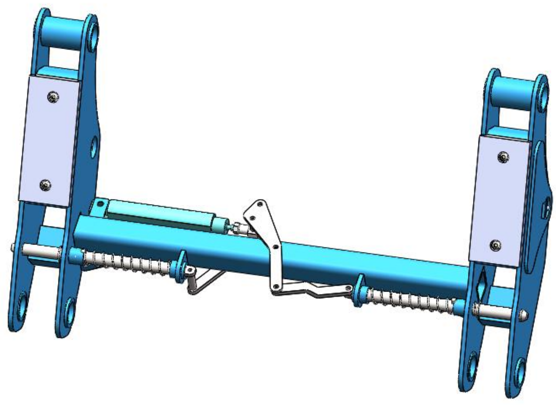


Fig. 6. The virtual quick hitch model - PIMR-BE archives
Rys. 6. Model wirtualny szybkosprzęgu – archiwum PIMR-BE

The preliminary design of the virtual model of loading transporter unit and the proposed changes to its structure were later subjected to kinetostatic and strength analyses. The test outputs allowed for the development of appropriate kinematics of the working space and a correct selection of design materials for the individual components of the loading transporter unit.

4. Kinetostatic analysis

Simulation research was carried out for a scenario, where the quick hitch of the loading transporter unit is aggregated with a mowing and raking unit (Fig. 7), a new tool module characterised by the highest weight. The virtual model of the loading transporter unit and tool module was subjected to a simulation taking into account the gravitation force for the defined materials used for specific design components, contact points of collaborating design elements, as well as friction forces occurring in the sliding runners of the shape sliding out from the support frame runners. In addition, time and stroke were defined for hydraulic servos used as part of actuation components, whose performance cyclogram is shown in Fig.8.

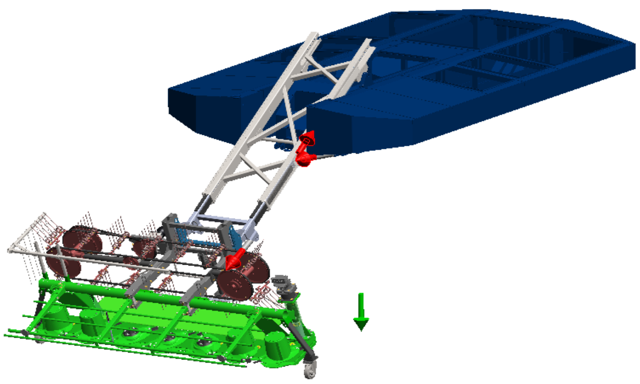


Fig. 7. The model during a simulation run for movement analysis - PIMR-BE archives
Rys. 7. Model w trakcie przeprowadzanej symulacji do analizy ruchu – archiwum PIMR-BE

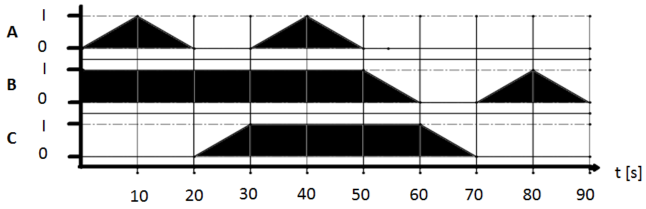


Fig. 8. Servo performance cyclogram: A – servos of quick coupling, B – servos of runner, C – servos of bearing frame – PIMR-BE archives

Rys. 8. Cyklogram pracy siłowników: A – siłowniki szybkosprzęgu, B – siłowniki prowadnicy, C – siłowniki ramy nośnej – archiwum PIMR-BE

The work character of the loading transporter unit can be presented as follows: in the initial position the servos of the bearing frame and quick hitch are unlocked, while the pistons of the runner servos are overdriven to the extreme positions. In these particular positions, the coupling process of the tool module from the ground level is simulated, where the servos of the quick coupling raise and move the tool module in such a way as to rest it on the fender plates of the working bracket. In this position, the locking pins slide out and protect the tool against accidental disconnection during protective operations carried out in the field. In the following sequence, the lowest position cutting range is analysed by lowering the tool module against the soil (ground). When the servos of the quick coupling return to their initial position, the servos of bearing frame lift the structure to the top working position, which is approx. 1.2 in the analysed case. In this position, the full tilt range against the ground level is analysed for the aggregated module, in a situation requiring the positioning of the module on the transportation trailer or in order to go round an obstacle during terrain manoeuvres. In the following step the runners are slid into the bearing frame as a result of overdriving the servos placed inside the side arms of the loading transporter structure. The loading transporter unit is lowered to its lowest position by the servos of bearing frame. In the last sequence, the required minimum force is tested to move the tools into the structure's bearing frame runners. In this position, the sliding working module is exposed to adverse forces, because of the smallest tilt angle of the loading transporter unit against the ground.

As a result of performed calculations (Table 1), the required values were obtained for the reaction forces of the working module on the quick hitch, which are shown in Figure 9, as well as reaction forces on the servos shown in Figure 10.

Table 1. The values of servo reaction forces at top and bottom fasteners, 40 sec work of loading transporter unit - PIMR-BE archives

Tab. 1. Wartości sił reakcji siłowników 40 s pracy wysięgnika dla górnego i dolnego zaczepu – archiwum PIMR-BE

Node	Force component Ry [N]	Force component Rx [N]
Bottom fastener of the quick hitch	-21,240	-14,370
Top fastener of the quick hitch	14,300	14,370

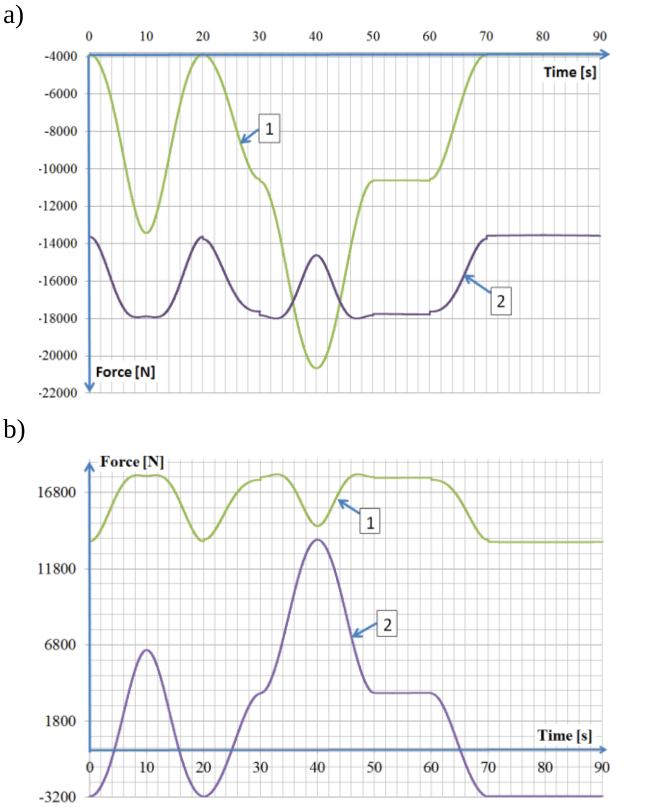


Fig. 9. The quick hitch reaction force components; a) top fastener, b) bottom fastener: 1 – force component Ry, 2 – force component Rx – PIMR-BE archives

Rys. 9. Składowe sił reakcji szybkosprzęgu: a) zaczep górny, b) zaczep dolny; 1 – składowa Ry, 2 – składowa Rx – archiwum PIMR-BE

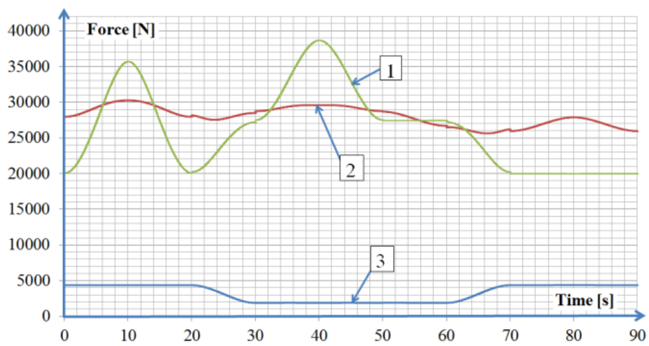


Fig. 10. Servomotor reaction forces for the set performance cyclogram - PIMR-BR archives

Rys. 10. Siły reakcji siłowników dla zadanego cyklogramu pracy – archiwum PIMR-BE

Based on the obtained graphs for the reaction forces in individual servos and reaction forces in quick hitch nodes, it was found out that the largest force values occur in the 40th second, i.e. when the tilt angle of the loading transporter unit against the ground is 14°, and the pistons of all servos are pushed out (Table 2). In this case, the bearing frame of the loading transporter unit is exposed to bending moment (approx. 685 Nm).

The data obtained in the simulation tests allowed for the selection of hydraulic servos and served the purpose of running a structural strength analysis.

Table 2. A breakdown of maximum values of forces occurring in specific servos - PIMR-BE archives

Tab. 2. Zestawienie maksymalnych wartości sił występujących w poszczególnych siłownikach – archiwum PIMR-BE

The values of servo reaction forces	Maximum force [N]
Servos of quick-coupling	38,68
Servos of runner	4,367
Servos of bearing frame	30,251

5. Strength analysis

The structural strength analysis for the new loading transporter unit and quick hitch versions was carried out with the use of finite element method.

In order to obtain a possibly low mass and ensure safety of loading transporter unit operations, the safety factor value for the whole structure was assumed as 1.5. In view of the above safety factor, material features were defined for specific design components. Structural steel Optim 500 was planned for the design of the bearing frame, quick hitch, runner and the top fastener of the loading transporter unit, and steel SS355JR was planned for components that are less stressed.

Thereafter, degrees of freedom were defined taking into account rotation and translation movements. The analysed model was restrained in the bottom part of the top fastener, at the fixing position on the tracked vehicle body; fixed geometry was applied. In addition, the movement of side runners sliding on the internal walls of the body was constrained by a virtual wall. Pin connections were allocated to individual nodes. In addition, frictionless contact was defined at the meeting points of the linear runners' slide block plates with the internal walls of the bearing frame beams of the loading transporter unit. The application of external forces (Fig. 11) was the final stage of defining the initial conditions for the analysed model of loading transporter unit .

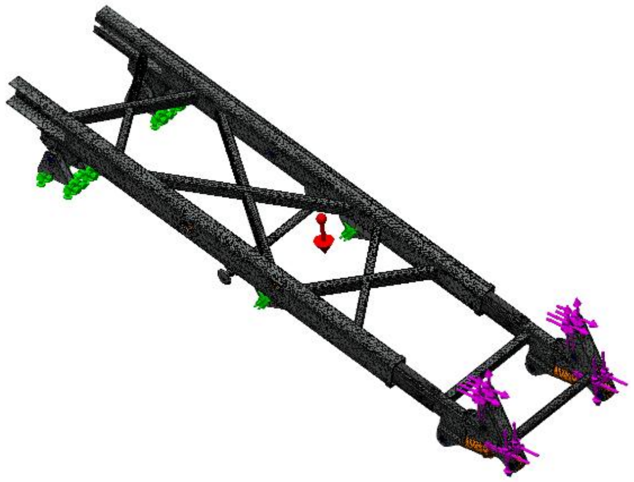


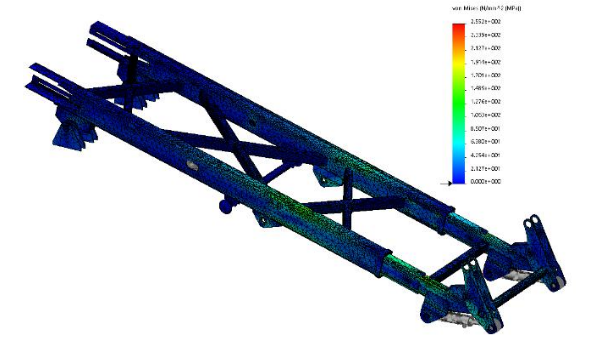
Fig. 11. The loading transporter unit model, initial conditions prior to strength analysis - PIMR-BE archives

Rys. 11. Model wysięgnika, warunki początkowe przed analizą wytrzymałościową – archiwum PIMR-BE

The simulation tests were run for two load variants of the loading transporter unit quick hitch. The first and second variant assumes the quick hitch to be aggregated with the working module, a mowing and raking unit with the largest mass at approx. 720 kg. The components of reaction forces applied by the working module, presented on a diagram generated by kinetostatic analysis, were distributed on both sides of the quick hitch: in a 3/7 proportion in the first variant, taking into account possible dynamic forces which may create an unequal distribution of forces on the quick hitch during the tracked vehicle fast movement on a rough and heterogeneous ground. In the second variant, the forces were distributed equally in order to simulate a regular operation of the loading transporter unit. The analysis was carried out for the most adverse scenario, where the working module exerts the biggest bending moment on the structure, i.e. for 40 sec. of the loading transporter unit operation.

The analysis results for the maximum von Mises stress and displacements in the first variant, are presented in Fig. 12, and the von Mises stress values for specific components are compared in Table 3.

a)



b)

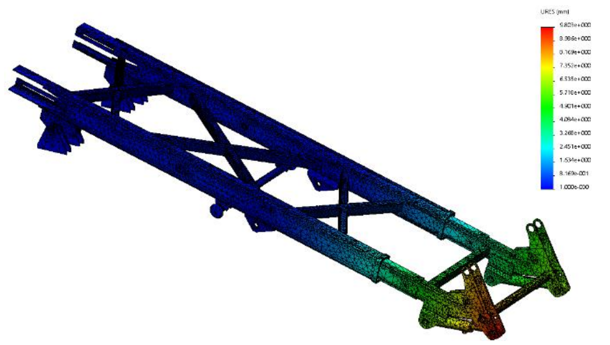


Fig. 12. The results of structural strength analysis for the first scenario: a) von Mises stress, b) displacement - PIMR-BE archives

Rys. 12. Wyniki analizy wytrzymałościowej konstrukcji dla pierwszego przypadku; a) naprężenia zredukowane, b) przemieszczenia – archiwum PIMR-BE

Table 3. Maximum von Mises stress for specific components of the loading transporter unit - PIMR-BE archives

Tab. 3. Maksymalne naprężenia zredukowane dla poszczególnych podzespołów wysięgnika roboczego – archiwum PIMR-BE

	Maximum von Mises stress [MPa]			
Analysed unit	Quick hitch	Runner	Bearing frame	Top fastener
Material	S355	OPTIM 500	OPTIM 500	S355
Scenario 1	161	230.1	255.5	44.1
Scenario 2	21.5	136.9	115.2	21.4
Average stress values	**91.25**	**183.5**	**185.4**	**32.7**

The highest values of Huber-Mises-Hencky stress are concentrated in the front of the bearing frame beam, in the location of furrows milled for the plate supporting the propelled drum and these values amount to 255 MPa. By analysing the displacement diagram it can be concluded that the most bend-susceptible component is the quick hitch. The bend value amounts to approx. 9 mm in this case.

Based on the values contained in Table 3 for the adopted value of safety factor at 1.5, the maximum values of von Mises stress for individual units read during the effort analysis do not exceed the allowed stress level for steel OPTIM 500 and amount to 312.5 MPa, while the boundary value for steel S355 is 230 MPa. In order to check fatigue strength, the average stress values and the maximum and minimum stress values obtained in computer calculations were compared with the Smith diagram for steel S355 (Fig. 13). After these values were plotted on the graph, it was possible to state that the values for the quick hitch, runner and top fastener fall within the range of boundary values of allowed stress, but these are slightly exceeded in the case of support frame. It needs to be noted that stress values in this particular point were compared to steel S355 characteristics (literature does not provide such characteristics for steel Optim 500), which features a lower fatigue strength of the parent material. The level of stress in this point must be absolutely reviewed by experiments.

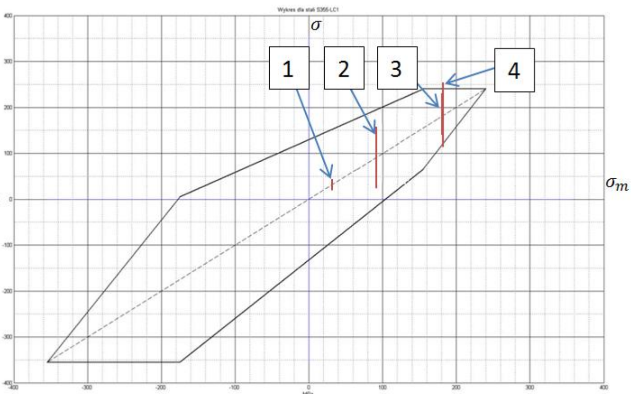


Fig. 13. The Smith diagram for steel S355 [4]. The maximum stress values compared to average stress for specific components: 1 - top fastener, 2 - quick hitch, 3 - runner, 4 - bearing frame

Rys. 13. Wykres Smitha dla stali S355 [4]. Maksymalne wartości naprężeń odniesione do naprężenia średniego dla podzespołów: 1 – zaczepu górnego, 2 – szybkosprzęgu, 3 – prowadnicy, 4 – ramy nośnej

6. Conclusions

The virtual models made for the new version of the loading transporter unit allowed for the following conclusions to be drawn:

1. The new version of the loading transporter unit meets all objectives of the project.
2. The change in the locking system with the use of a pneumatic servomotor improves the functionality of tool modules aggregation with the loading transporter unit.
3. The new design makes it possible to lower the loading transporter unit down to 30 cm above the ground, and thus enables the tool module to be coupled from the ground level and to mow aquatic vegetation in a range of 1 - 2 m below the water surface.
4. The real model of the loading transporter unit will be tested in field trials planned for the turn of 2014/2015.

7. References

[1] Research project No. WND_POIG.01.03.01-00-164/09: Zintegrowana technologia ochrony obszarów wodno-błotnych przed sukcesją roślinności powodującej degradację środowiska przyrodniczego (Integrated technology to protect wetlands against vegetation succession resulting in degradation of the natural environment), Project Manager – K. Zembrowski, 2010-2014.

[2] Dubowski A.P., Zembrowski K., Rakowicz A., Pawłowski T., Weymann S., Wojniłowicz Ł.: Developing new-generation machinery for vegetation management on protected wetlands in Poland, Mires and Peat: http://mires-and-peat.net/pages/volumes/new-articles.php.

[3] Mikołuszko W.: Ochrona przed ochroną. Tygodnik Powszechny, 10, 19-03-2014.

[4] Szczepaniak J., Rogacki R., Szczepaniak M., Mac J., Wasieczko P., Grzechowiak, R., Wojciechowski J., Pawłowski T.: Agregat uprawowo-siewny z mechatronicznym układem sterowania umożliwiającym zwiększenie prędkości roboczej i podwyższenie dokładności wysiewu (Tilling and sowing unit with a mechatronic control system to raise the working speed and improve sowing precision) Task 10, PIMR, Poznań, 2014.

[5] Zembrowski K., Dubowski A. P., Stobnicki P.: Pojazdy do zbioru i transportu biomasy na chronionych terenach bagnistych - ocena ich pracy i oddziaływania na środowisko naturalne. Konferencja Logistyka w Ratownictwie (Vehicles for biomass mowing and transportation in protected wetlands - assessment of their performance and impact on the natural environment. Conference on Rescue Logistics), Suwałki, CD no. 1, Logistyka, 4/2014.

[6] Zespół wysięgnika roboczego, zwłaszcza rolniczego pojazdu gąsienicowego przeznaczonego do pracy w terenie wodo-błotnym (Loading transporter unit, especially in agricultural tracked vehicle for use in wetlands), PIMR - Patent P.398042. (in Polish).

[7] http://www.hydromega.com.pl/

[8] http://www.ensinger-online.com/

[9] http://www.solidworks.com/