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# The use of numerical methods in cutterhead dredger excavation unit optimization

*Authors presented a numerical approach for assessing the efficiency of the cutterhead dredger. To assess the efficiency parameters, it was necessary to determine the boundary conditions such as the geometry of the cutterhead, which was obtained by 3D laser scan and operational parameters of the dredger. Based on that numerical model was prepared to and numerous analyzes conducted that allowed authors to verify their thesis regarding the improvement of the machines efficiency, proposing the correct teeth geometry on the cutterhead and at the same time gave the opportunity to determine their optimal alignment for a specific work technology.*

***Keywords:*** *: dredger, Rigid-Body Dynamic, 3D scanning*

## 1. INTRODUCTION

Mining, rock/raw materials processing or material handling is dominated by the underground and surface mining technologies. One should also be aware that exploration of minerals or earth moving is undertaken also under water. It can be very demanding and sophisticated deep, open water mining but also removing, collecting or relocating material from relatively shallow water which is called dredging. Dredging is the process which is very often a part of maintaining the ports, channels and other water passages to keep them accessible. However, as already mentioned, collecting of sediments, but also more hard or cohesive soils are run that way.

As the dredging is used in different basins and for different type of minerals, dredgers – the special type of floating excavators, differ in construction of the floating unit and working/excavating unit.

From the point of view of the floating unit, the main type division is for self-propelled and stationary. Self-propelled units are similar to regular vessels which are able to change the location in long distance, seagoing. However, for the change of the local position while operating piles and anchored ropes are in use.

Stationary, non-propelled are the barge floating structures which requires independent units engagement in purpose to relocate. Mostly, those units are smaller. The local change of the position, while operating, is provided by piles and anchored ropes or anchored ropes only.

The classification with respect to the working unit is strongly related to the collected material and its resistance for excavation. Both the factors will influence the collection/suction method and dislodgement method. For the purpose of this article only the excavating units for hard minerals will be discussed.

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While facing with the cohesive soils or hard mineral a cutterhead must be installed. Cutterhead function is similar to all mining equipment cutting tools where hard rock or soil must be excavated.

Most common cutterhead is the *crown type*. Crown design will differ with respect to the resistance of the excavated material. A *wheel type* cuter is similar with its construction to all bucket wheel excavator/reclaimers operating on the surface. A modification of this type is closely spaced bucket wheel which works like milling cutter or cutting blade **Błąd! Nie można odnaleźć źródła odwołania.**.

In the presented paper, investigations of technological parameters with respect to the production output of the non-propelled dredger will be discussed. Excavating unit of the machine is bucket type cutterhead, however of special two side/blade with closely spaced buckets. As a result the cutting tool is closer with is function to milling type cutting blade. In figure 1, the barge on which the system is installed is presented with the cutting blade in the foreground.

**Figure 1. View of the dredger**

The manoeuvrability is provided by sets of anchored (at the dry shore) ropes operate by winches. Two of the ropes are assemble to the dredger ladder providing slewing. Set of three ropes running to the common point localised at stern, creates the fixed point of rotation. For location change in big range, external self-propelled unit must be used. Presented machine is used for underwater sand excavation.

## 2. PROBLEM IDENTIFICATION

It is common problem that the underwater sand excavation faces two main problems related to wear of the cutterhead and relatively low output. Both issues are more present in heavy operational conditions (high excavation/cutting resistance). Despite such a heavy conditions, the conventional dredging technique with cutter head is still used as more economically efficient instead of blasting based technique. This is due to the fact that not all sand deposits are characterised by high cutting resistance that can be excavated with satisfactory output and equipment wear ratio. However more and more deposits, which are scheduled for excavation lately, are these, where abrasive wear and low output play an important role in the total cost of operation. Therefore it is important to design new and optimise existing dredging equipment to enable operation in the wider range of excavation resistance with economically justified costs. For this purpose investigations of cutting tools wear process based on operational data, experimental tests and numerical simulations were conducted. Based on the results of investigations, optimisation recommendations of cutting process are given. The presented approach is applied for dredger described in the first chapter of the paper however it can be used at any dredging equipment a well.

### 2.1 Cutting tool wear process

In the described dragger, which is equipped with two bucket wheels on which chisel type teeth are installed, the wear process occurs on the cutting edges of teeth at the most and on the bucket wheel as well. Example of teeth wear process is shown in figure below.

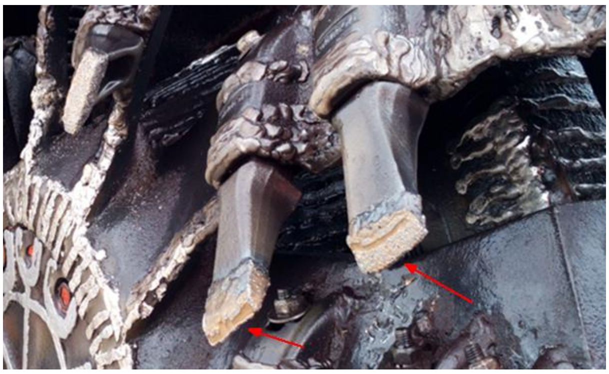

**Figure 2. Typical wear of cutting teeth**

The abrasive wear of teeth is typical for sand excavation and accelerated by higher excavation resistance of deposit. In order to improve teeth usage intervals all areas, which are prone to such abrasive wear are hardfaced (around 60 HRC hardness is obtained). The same technique is used to prevent wear of the bucket wheel in teeth fixing areas and buckets edges as well. The wear rate of teeth is significantly high and requires replacing of around 20-30 % of teeth per 24 hours of operation. Teeth are then repaired by hardfacing of cutting edges. Teeth wear is unequal and the higher wear rate is observed on the corner located teeth and also on the teeth fixing areas (Figure 3).

**Figure 3. Unequal wear of teeth and bucket wheel wear areas**

Unequal and asymmetric wear observed on the cutter head indicates improper design of cutting geometry such as locations, numbers and angles of teeth. In order to analyse this phenomena in details, the 3D laser scanning, loads identification and further numerical simulations were conducted.

### 2.2 Laser scanning

Due to the need to accurately simulate the dredging process, a virtual model of cutterhead was developed [1]. The model was created using a 3D scanning technique. The overall scanning accuracy was 3 mm at 50 m and angular accuracy of 8 "horizontally and 8" vertically. Scans were made in five positions: 0°, ±45°, ±90° in relation to the cutterhead boom longitudinal. An example view on the scanning object and equipment is shown in Figure 4 and 5.

**Figure 4. First scanning position - 90°**

**Figure 5. Second scanning position - 45°**

Based on the surface model, generated from the cloud of points, a solid model of the cutterhead was developed. This 3D scan model of the cutterhead was compared with the virtual 3D model created with consideration of technical documentation. Comparison of both models is shown in Figure 6. Significant differences were found, which means that the existing cutting wheel has not been built as per design, which is caused by low quality or errors of casting process of the cutting wheel.

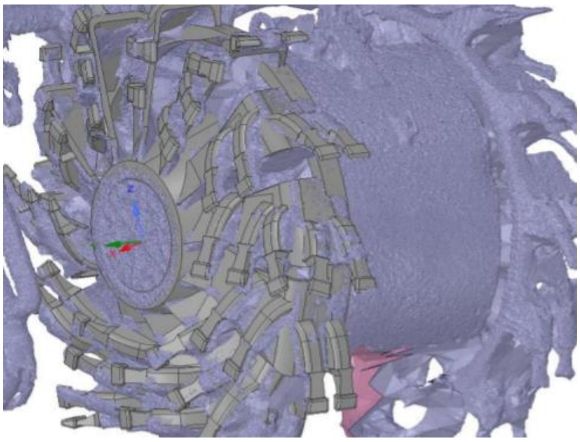

**Figure 6. Comparison of 3D scan and the model created with consideration of technical drawings**

The model obtained thanks to 3D scanning has been implemented for further numerical calculations as a reference to the real object. On the basis of this model, a kinematic analysis of the cutterhead and ladder was made. The trajectory of tooth movement during the dredging process were determined as well [14].

### 2.3 Loads identification

The main operational loads are generated by slewing (movement generated by two winches which ropes are attached to the ladder in the proximity of cutterhead) and cutting wheel rotation. Both drives are powered by hydraulic system of maximum operational pressure of 200 bars.

In Figure 7 trace of the cutting wheel pressure and output(tonnes per hour) is presented. One can observe that output drops and rise are not correlated directly with the pressure increase, with exception to the time band 400-600s where cutterehead is out of the excavated deposit.

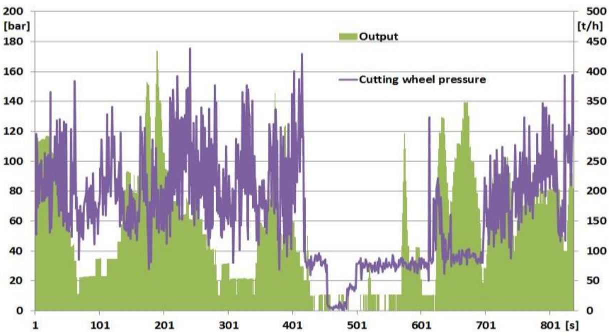


**Figure 7. Cutterhead pressure and output trace**

Analysis of Figure 8 allows to observe that nevertheless the slewing force (generated by the hydraulic winch) is kept relatively constant, there is no constant value of output observed. The only relation observed in two cycles, is increase of the output with pressure increase (with small phase shift), but only in the end of slew cycle (~190s., ~290s).

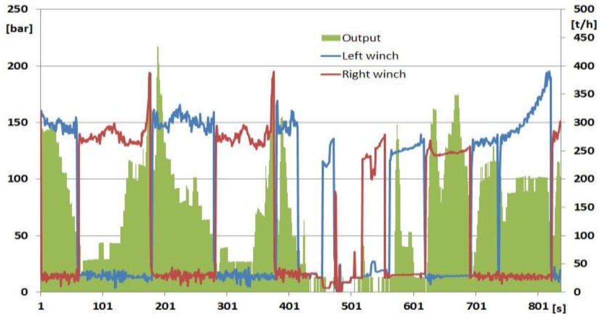


**Figure 8. Cutterhead winch pressure and output trace**

In Figure 9 where pressure of slewing and cutting is compared, it is possible to point that alternations of cutting wheel pressure are close to harmonic and not reaching the maximum value. Different observation is done in case of the slewing winch pressure which is rather constant, but rapid increase of the pressure (up to the maximum value) are observed occasionally.

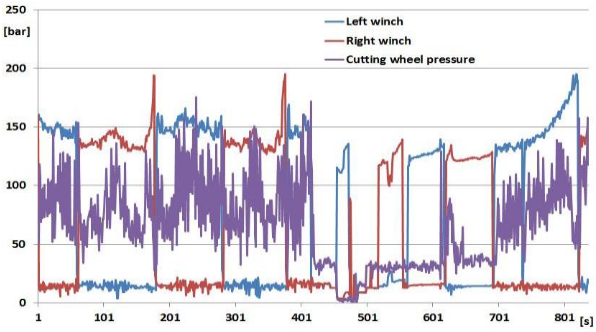


**Figure 9. Cutterhead winch pressure and cutting wheel pressure trace**

The analysis of diagrams described above, drives the conclusion that process of operation is not stable. Fluctuations of resistance increase, not correlated with the output increase, implies the difficulties with excavation process. Rapid pressure rise at the slewing winches, confirms problems with operation – emergency stops. The expected output (300 t/h) is reached only occasionally.

Measurements of forces on the winches ropes indicated that forces during normal operation oscillates around the value of 60-70 kN. When overload, the force in rope reaches about 80 kN. If assuming that the nominal excavation torque on the wheel (21kNm) corresponds with the maximum hydraulic pressure of the wheel drive, the average operational torque equals 7.9 kNm.

## 3. NUMERICAL SIMULATIONS

In author's method, in order to determine the efficiency of the dredger, numerical methods were implemented [16][17]: Discrete Element Methods (DEM) and Rigid Body Dynamics (RBD). Authors proposed to determine the efficiency of the dredger as a measure of the change in the load of the cutterhead, thus changing the loads on the cutterhead and the ladder.

By means of the RBD analysis, the trajectories of the teeth were determined [9]. The simulation was carried out in accordance with the parameters of the real object [2][7][8][10]. Thanks to the implementation of the Discrete Elements Method, excavated material model has been built [11][12][15]. The correctness of this model was verified by means of a comparative analysis of numerical simulation loads and operational loads described in subchapter 2.3 [5][6]. The values of the loads from the simulation were compared with values measured on the real object [3][13]. Parameters related to the contact between discrete elements have been adjusted to properly calibrate the numerical model [18]. As a result the validated numerical model was use as a reference to subsequent numerical DEM-RBD simulations, allowing to determine the method of improving the dredger's efficiency. The RBD and DEM model described above is shown in Figure 10, where dredging process is simulated.

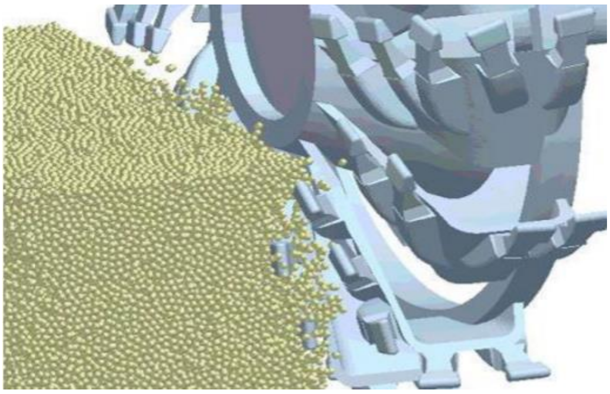

**Figure 10. Simulation of RBD-DEM**

Figure 11 presents examples of teeth trajectories obtained from simulations as well.

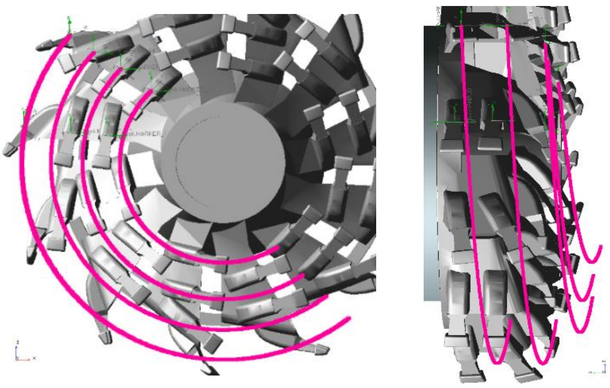

**Figure 11. Teeth trajectories of RBD-DEM model**

## 3.1 Currently used cutterhead

Numerical simulation with current teeth geometry were performed. Diagrams of torque loads measured on the cutterhead shaft and ladder are shown in Figures 12 and 13.

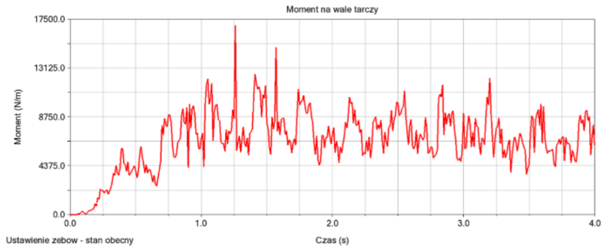


**Figure 12. Torque load of the cutterhead shaft**

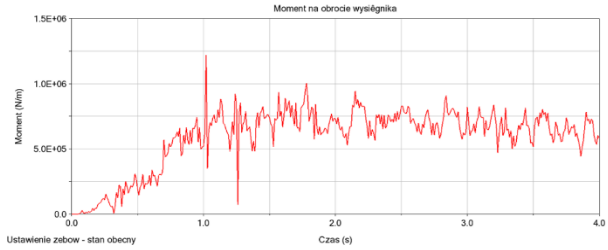


**Figure 13. Torque load of the ladder**

The effective reference values of the obtained characteristics were determined. Torque on the cutterhead shaft equals (1):

$$RMS_{S0c} \cong 8\,477 \text{ Nm} \tag{1}$$

Torque on the ladder equals (2):

$$RMS_{S0L} \cong 783\,220 \text{ Nm} \tag{2}$$

## 3.1 Optimisation of the cutterhead

Based on the numerical simulations of the existing design, the new geometry of teeth locations and angles were developed (Figure 14), and numerical simulation were performed to obtain optimal solution. Diagrams of torque loads for the cutterhead shaft and the ladder for the existing and new model are shown in Figures 15-16.

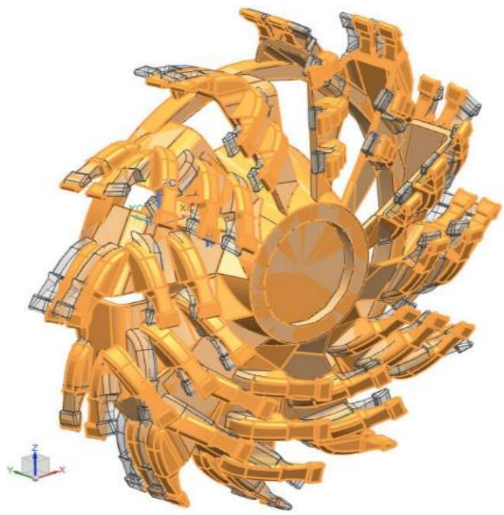

**Figure 14. The new model (orange) compared to the existing one**

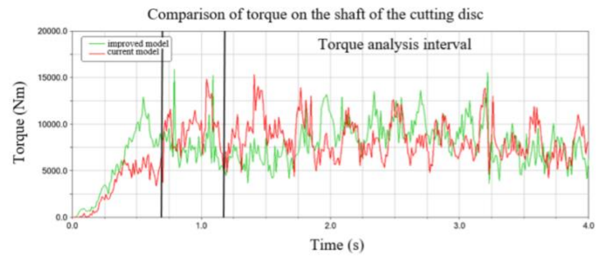


**Figure 15. Comparison of exisitnig and new design of teeth geometry- torque loads on the cutterhead shaft**

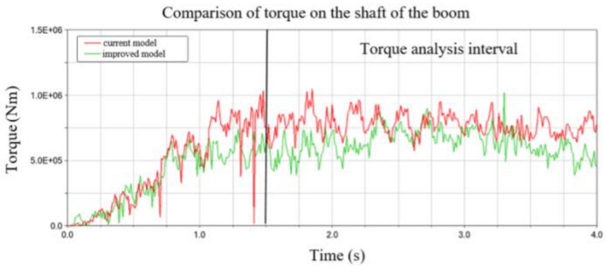


**Figure 16. Comparison of existing and new design of teeth geometry- torque of loads on the ladder**

The effective reference values of the obtained characteristics for the new geometry were determined. Torque on the cutterhead shaft equals (3):

$$RMS_{S1c} \cong 8\ 691\ \text{Nm} \tag{3}$$

Torque on the ladder equals (4):

$$RMS_{S1L} \cong 641\ 070\ \text{Nm} \tag{4}$$

## 4. EXPECTED INCREASE OF THE DREDGER OUTPUT

As per simulations results, the significant drop of torque loads (~18%) on the ladder was observed for the new design in comparison to the existing one, while the load on the cutterhead shaft remains almost unchanged. With such a results it is possible to increase slewing speed of the ladder and obtain output increase as well within existing torque limits of the dredger. Increase of the dredger output can be assumed as volume of the material being excavated while slewing of the ladder in the unit of time for the existing and higher slewing speed.

In order to obtain optimal geometry of the new design, numerical simulations with different position angles of teeth in relation to the model exhibiting lower resistance forces, were performed. It was decided to deviate the teeth in the positive and negative angles in relation to the corrected model to. This approach enabled finding the minimum torques loads on the ladder and cutterhead shaft and thus the optimal angle of tooth position on the bucket wheel of the cutting disc. The obtained results for three different teeth angles allowing to determine the optimal value are shown in Figures 17 and 18.

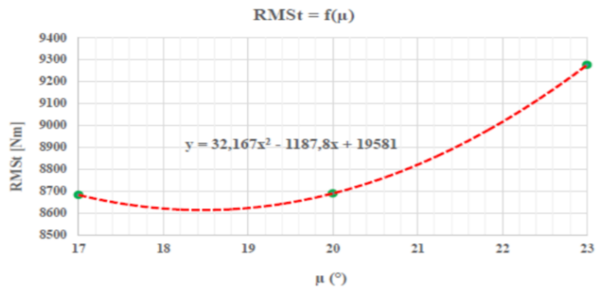


**Figure 17. Teeth angle vs cutterhead shaft torque**

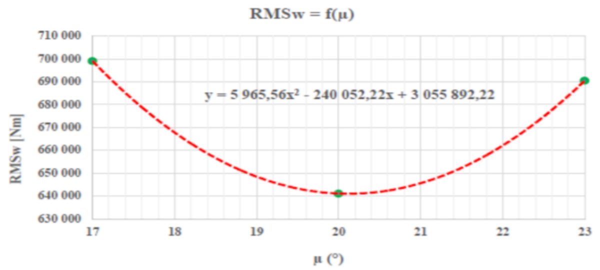


**Figure 18. Teeth angle vs ladder torque**

The obtained torque loads results were approximated with the quadratic polynomial The function minimum for cutterhead torque equals 18.5°, while for the ladder torque it is 20°.

In the next step similar type of simulations were performed with increased slewing speed of the ladder for 18%. Both ladder and cutterhead torques were checked for the constant teeth angle of 20°. As per obtained results the torque on the cutterhead shaft equals (5):

$$RMS_{S1c} \cong 9\ 487\ \text{Nm} \tag{5}$$

Torque on the ladder equals (6):

$$RMS_{S1L} \cong 658\ 330\ \text{Nm} \tag{6}$$

Based on the results it was confirmed that optimized teeth geometry enabled to increase output of the dredger without significant loads of the machine. Expected increase equals 15%.

## 5. SUMMARY AND CONCLUSIONS

Dredging of mineral deposits faces problems related to wear process of cutting tools. Such problems are accelerated by excavation of deposits characterised by high excavation/cutting resistance, which directly impacts production output. In order to improve this situation it is possible to design new technical solutions or optimise existing ones. Authors of this paper present numerical and experimental approach to optimise geometry parameters of dredger's cutterhead in order to increase output and reduce unequal wear of cutting equipment.

The analyses conducted for the existing design pointed out that actual geometry of cutting tool is not suited for the operational conditions. Maximum capacity of the side winches is reached repeatedly with no dredger output increase. Additionally, problems with rapid cutting teeth wear and its insecure assembly, increase the machine downtime. As a result, the total output is far from the expected. In order to improve this situation, the new optimised geometry of cutter head was developed. In the new design locations and teeth angles were modified and numerically tested with the use of Discrete Element Methods (DEM) and Rigid Body Dynamics (RBD) methods.

In the presented in the paper case of the sand dredger and with consideration of the results of the numerical simulation it was possible to estimate that the potential of the output of the dredger is not achieved. By implementation of the optimised design of cutting tools, it is expected to increase the excavation efficiency for even up to 20% and a the same time to increase output of the dredger significantly within existing drives limits.

As a result of the performed investigations the following conclusions can be given:

1. Dredging of new deposits, with more difficult excavation conditions, results in many problems such as higher wear rate of cutting tools and lower output, which may lead to situation where existing technique use is not economically justified anymore.
2. In such a case optimisation of existing technique may extend operational limits significantly.
3. The design of the cutting tools should be customised with respect to the material type (characteristics, resistance) and the technical capabilities of the dredger.
4. Numerical methods are efficient tools to simulate, and investigate cutting process and thus enable to obtain optimised solutions.

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