Bucket wheel rehabilitation of ERC 1400-30/7 high-capacity excavators from lignite quarries

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Abstract. The existence of bucket wheel equipment type ERC 1400-30/7 in lignite quarries with lifetime expired, or in the ultimate life period, together with high cost investments for their replacement, makes rational the efforts made to rehabilitation in order to extend their life. Rehabilitation involves checking operational safety based on relevant expertise of metal structures supporting effective resistance but also the replacement (or modernization) of subassemblies that can increase excavation process productivity, lowering energy consumption, reducing mechanical stresses. This paper proposes an analysis of constructive solution of using a part of the classical bucket wheel, on which are located 9 cutting cups and 9 chargers cups and adding a new part so that the new redesigned bucket-wheel will contain 18 cutting-chargers cups, compared to the classical model. On the CAD model of bucket wheel was performed a static and a dynamic FEA, the results being compared with the yield strength of the material of the entire structure, were checked mechanical stresses in the overall distribution map, and were verified the first 4 vibrating modes the structure compared to real loads. Thus was verified that the redesigned bucket-wheel can accomplish the proposed goals respectively increase excavation process productivity, lowering energy consumption and reducing mechanical stresses.

1. Introduction
The existence of bucket wheel equipment type ERC 1400-30/7 (figure 1) in lignite quarries with lifetime expired, or in the ultimate life period, together with high cost investments for their replacement, makes rational the efforts made to rehabilitation in order to extend their life.

Rehabilitation involves checking operational safety based on relevant expertise of metal structures supporting effective resistance but also the replacement (or modernization) of subassemblies that can increase excavation process productivity, lowering energy consumption, reducing mechanical stresses [1].

An essential subassembly of these machines is the drum shedder, component of driveline composed of bucket-wheel, shaft and gearbox. So this subassembly is subject to rehabilitation and modernization by redesign, since is the main part of the equipment that can increase excavation productivity. Drum shedder type excavator machines with high capacity for lignite quarries, model Erc1400 were installed first time in Romania in 1970. So they are widely used and proved that are reliable equipment [2].

Consequently the drum shedder and its driveline will be subject to CAD modeling and FEM analysis as steps to modernization and replacement.
2. Modelling of the drum shedder subassembly

2.1. Subassembly CAD modelling
For correct modeling of studied subassembly must be analyzed the main cinematic chain [3]. Acting drum shedder powertrain consists of an electric motor – cardan joint shaft - gearbox, as shown in figure 2.

The main element that gives machine productivity is drum shedder and its main component elements, respective cutting cups (pos. 8), and chargers cups (pos. 9), cf. figure 2 [4]. Drum shedder is a subassembly with a mass of about 30 tons (figure 3) and that in the early stages of the modernization process is to totally removed, meaning drum shedder, its cups and wheel shaft.
This paper proposes the analysis of a new constructive solution based on the use of part of the classic drum shedder (figure 3), with its components and bearings supporting the shaft and placing a new ring (figure 4), containing combined cutting / chargers cups, attached to the classic rotor.

Before machining, after removing the subassembly of drum shedder and placing of ring with cutting / chargers cups, will be performed an expertise on all drum shedder subassembly, by non-destructive testing of welds, but also analysis and tests necessary to determine the capable load of material.

Thus was CAD modeled the classic drum shedder, and wheel shaft also. Modelling shaft is also necessary because the classic conical-cylindrical gearbox will be replaced with a new one conical-planetary, whose main advantage is that is lighter than the classic one.
CAD modeling has led to the geometric model (figure 5), where 1-shedder wheel shaft assembly, modeled with new gearbox as well as classic model of assembling rotor bearings; 2-wheel ring with cutters/chargers cups, that will be fitted on the wheel cone (pos. 3), using elements 4 - 4’ that will finally permits attachment to the classic part of the rotor (pos. 5). Fasteners 4 and 4’ ensure both the connection between the old and the new part of the wheel but also the protection against deposits of excavated material inside the rotor.

![Figure 5 Modernized rotor](image)

After completing shedder wheel subassembly (item 2, figure 6), this is mounted on the arm shedder (1), through two bearings: one fixed on classic part of the arm and one mobile (item 3) on the auxiliary metallic construction (pos. 4) on which is arranged the cinematic rotor drive. This auxiliary metallic construction may have a form optimized for fulfilling the criterion of stability and structural strength but also for optimum gripping of cinematic assembly.

![Figure 6. Attaching wheel on the arm shedder](image)
2.2. MEF analysis of drum shedder subassembly

The second stage contains static and dynamic analysis, highlighting their modes of vibration for modernized drum shedder [5].

In the process of excavation, on the assembly tooth - bucket – rotor - shaft acts cutting force components, which are shown in figure 7, considering the reference system of the rotor.

![Figure 7. Cutting force components](image)

Where:
- $F_y$ - tangential force (cutting) - excavation force;
- $F_x$ - radial force, imposed by the moving mechanism and maintaining consistently the equipment in excavation;
- $F_z$ - lateral force to advance.

The main source of vibration to an excavator is the time fluctuations of the three components of excavation force, being not synchronous to the fundamental frequency of coming into excavation of the cups.

Time variation of excavation component forces is caused by variations in mechanical properties of the layer of coal and uneven wear of cups tooth, which makes the fundamental frequency of perturbation to approach the bucket wheel rotation.

It’s been calculated the excitation frequency (excavation) for two types of rotor, classic and upgraded (modernized), depending on the number of cups placed, but also shedder wheel speed $n_{rc}$ with the relationship [5]:

$$f_e = \frac{n_{rc} \cdot z_c \cdot (\pm 20\%)}{60} \text{ [Hz]}$$  \hspace{1cm} (1)

It can be established the following frequencies, table 1

| Drum shedder turation [rot/min] | Number of cups | Excitation frequency [Hz] (Excavation frequency) |
|--------------------------------|----------------|-------------------------------------------------|
| Classic Rotor 4.32 | 9 cutting cups, 9 chargers cups | $f_e = \frac{n_{rc} \cdot z_c}{60} = \frac{4.32}{60} \cdot 18 = 1.296 \text{ Hz} \cdot (\pm 20\%) = (1.037\ldots1.555) \text{ Hz}$ |
| Modernized Rotor –var I 4.68 | 18 cutting / chargers cups | $f_e = \frac{n_{rc} \cdot z_c}{60} = \frac{4.68}{60} \cdot 18 = 1.56 \text{ Hz} \cdot (\pm 20\%) = (1.123\ldots1.684) \text{ Hz}$ |
| Modernized Rotor –var II 4.68 | 20 cutting / chargers cups | $f_e = \frac{n_{rc} \cdot z_c}{60} = \frac{4.68}{60} \cdot 20 = 1.60 \text{ Hz} \cdot (\pm 20\%) = (1.248\ldots1.872) \text{ Hz}$ |
This calculation was performed to see the range where to integrate FEM model of the modernized wheel shedder, i.e. the number of cups to be arranged.

For static structural calculus are considered the following hypotheses:
- To the hub bucket, namely the bushing used for mounting driveshaft, is applied the output torque of the gearbox, considered as acting torque for drum shedder;
  
For this modernized gearbox the torque is approx. 1337 KNm, which according to DIN 22261/2 must be multiplied by a factor of 1.5, so the calculus torque is:

$$M = 1.5 \times 1337 = 2005.5 \text{ KNm} \quad (2)$$

- Disposal of fixed supports on the cutting side of drum shedder for 1/4 of the total number of cups (for 18 cups and 20 cups). We apply this condition on the same number of cups, respectively 5 cups.

Structural-modal analysis by applying FEM involves classical three steps: pre-processing, structural-modal calculus and post-processing, by highlighting results [6].

1. Preprocessing consists of:
   1.1 - Establishing the type of material for the structure - S355 J0 [7];
   1.2 - Verifying CAD model and importing in FEM software, figure 8.a, b;
   1.3 - Meshing the model with tetrahedral higher order elements since are discretized curved surfaces, figure 8. c;

![Figure 8.a CAD model (phase)](image)

![Figure 8.b CAD model - detail](image)

![Figure 8.c Meshing the model with tetrahedral higher order elements](image)
1.4 - Specifying supports layout:
- It's considered fixed seating on the driveshaft bearings for modal analysis, figure 9.a;
- It's considered fixed seating on excavating part for 5 cutters cups for static analysis, figure 9.b

![Figure 9.a Supports layout - modal analysis](image)
![Figure 9.b Supports layout - static analysis](image)

1.5 - Specifying loads:
- For modal analysis is specified gravitational loading $G = 9.81 \, \text{m/s}^2$, figure 10.a (pos.1);
- For static analysis is specified torque $M = 2005.5 \, \text{KNm}$ (pos.1) and gravitational acceleration (pos. 2), figure 10.b.

![Figure 10.a Loads - modal analysis](image)
![Figure 10.b Loads - static analysis](image)

2. Structural-modal calculus (static and dynamic analysis) is achieved through the specific FEM computer software, with a specified degree of convergence.
3. Postprocessing - highlighting and interpretation of results for the two models considered respectively with 18 and 20 cups cutters / loading and interpretation of distributions of stresses and deformations.

Further it was adopted following criteria:
- for static analysis - Establishing equivalent Von Misses stress and comparing the maximum value with minimum yield for S 355 J0, the material used for making analyzed subassembly.
- for modal analysis - frequency of first vibration mode to be higher than the frequency calculated, according to table 1.

The Von Misses stress distributions are presented in figure 11 a, b for drum shedder with 18 cutters / loading cups respectively for drum shedder with 20 cutters / loading cups, and in figure 12 a, b the displacement distribution for the 2 variants of drum shedder (18 cutters / loading cups and 20 cutters / loading cups).

![Figure 11.a Stress distribution – 18 cups](image1)

![Figure 11.b Stress distribution - 20 cups](image2)

![Figure 12.a Displacement distribution – 18 cups](image3)

![Figure 12.b Displacement distribution - 20 cups](image4)
Values of equivalent stress and displacement for the 2 variants are:

\[ \sigma_{VM\ 18} = 60.85 \text{ N/mm}^2 \quad \sigma_{VM\ 20} = 144 \text{ N/mm}^2 \]
\[ \delta_{st\ 18} = 1.246 \text{ mm} \quad \delta_{st\ 20} = 3.08 \text{ mm} \]  \hspace{1cm} (3) \hspace{1cm} (4)

Results for modal analysis, meaning deformed shape and frequency for the first three natural vibration modes are presented in figures 13 a, b, c for 18 cutters / loading cups and figure 14 a, b, c for the second variant of drum shedder with 20 cutters / loading cups.

Figure 13.a Mode 1=5.357 Hz     Figure 13.b Mode 2=1.909 Hz  Figure 13.c Mode 3=1.191 Hz

Figure 14.a Mode 1=5.487 Hz     Figure 14.b Mode 2=1.940 Hz  Figure 14.c Mode 3=1.196 Hz
Conclusions

a. Static analysis – it can be seen that for both variants the equivalent Von Misses stresses do not exceed the yield strength of the material of drum shedder. Instead, for the 20 cups rotor, the equivalent stress is significantly larger:

\[ \sigma_{VM,20} = 144 \text{ N/mm}^2 > \sigma_{VM,18} = 60.85 \text{ N/mm}^2 \] (5)

This mechanical tension, for a large number of operating cycles, can lead in the end to cracking in places with high stress [8].

In practice, checking the rotors that are made with caisson type rings, like the one considered for our case, it was observed that cracks appears exactly in the clamping area of the cups on this ring, as shown in figure (photo) 15.

![Cracks in areas heavily strained ring rotor](image)

Figure 15. Cracks in areas heavily strained ring rotor:
1- grip ear cup, 2- rotor ring crack

b. Modal analysis - considering the way of functioning during excavation and deformed shape of the rotor, it will be considered frequencies of vibration modes 2 and 3. From this point of view there aren’t large differences between the two constructive types of rotors, and the displacements for respective modes are small.

Comparing the results obtained for the two types of rotors we can conclude that the rotor with 18 cups is the constructive version that will be adopted. Even if tensions in the ring zone are small compared with the 20 cups version must be considered the clamping mode and thickness required for ring caisson.

Some other advantages of this constructive version are:
- Recovery of classic rotor material about 50-60%;
- Reduction of rotor vibration that occurs for membrane constructive version.
- Decreased deposition of material inside the rotor by disposing inside a protective ring.
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