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DETERMINATION OF LOAD SPECTRUM OF BUCKET WHEEL EXCAVATOR SRs 1300 IN COAL STRIP MINE DRMNO

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Summary

Toothed gear power transmissions are complex mechanical systems and their design is a very challenging engineering task that requires the application of common calculation procedures and contemporary designing methods. Operating conditions of the gear power transmission are important for the design process from the aspect of overload prediction and they are defined within the design process by the operating condition factor K_A, which has a wide range of values (1 to 2.5), prescribing various operating situations. However, a good design of the toothed gear power transmission can be achieved if operating conditions are simulated and as such implemented in the calculation/design procedure. Such improvement in the design process can be done with the use of defined load spectra that accurately describe realistic operating conditions. The paper presents the results of tensiometric measurements of torque at the output shaft of the working wheel gearbox of the bucket wheel excavator SRs 1300 TAKRAF in the coal strip mine Drmno, and gives a definition of appropriate load spectra based on these tensiometric measurements. The load spectra are defined by applying the full cycle discretization method and as such afterwards used for the calculations/design of the working wheel of the bucket wheel excavator (gears, shafts, shaft keys etc.).

Key words: *power transmission, bucket wheel excavator, working wheel, load spectrum*

1. Introduction

A large number of complex machine systems (MS) operate under highly variable exploitation conditions and their components/parts are exposed to variable loads, i.e. strain, which is usually stochastic. Exploitation requirement set down in the design process is that each MS has certain operational safety and reliability for a given lifetime span. However, the effect of, for example, variable strain with sufficient intensity and duration can damage some vital parts of the MS and failures of the MS can occur. Damages or failures of parts manifest themselves in excessive and permanent deformations, static or violent fractures, dynamic fracture caused by fatigue, increased wear, corrosion, overheating etc.

Monitoring of a complex MS in non-stationary operating conditions is a typical engineering issue. Depending on the machine complexity, the type and the intensity of the fault to detect, the nature of load variation, etc., different methods and approaches are used to provide adequate results [9-11].

The modern concept of design and calculations of complex and usually very expensive MSs includes making a detailed model. This model should cover the calculation based on the determination or assessment of safety, lifetime, and reliability of both component and the system on the basis of real MS exploitation conditions. The most important factor in terms of safety and reliability of a MS (such as the working wheel drive transmission of the bucket wheel excavator) is the carrying capacity of its structural elements. The carrying capacity can also be considered as a measure of the transmission part's quality [1, 2]. The calculation of the carrying capacity is accomplished by comparing the working and the critical load states in the transmission elements and the evaluation of the quality is reduced to the evaluation of the accuracy of values of working and critical stresses. The accuracy of the estimated working loads depends on the appropriateness of the applied methods and the determination process. The appropriateness of a method is determined by its potential to identify the status, place and intensity of the highest stresses/loads and the quality of applied methods is verified through experiments. The value of working stress depends on loads, thus it is necessary to know real values of the load in operation conditions. Therefore, it is necessary to know the intensity, course of change, frequency as well as probability of occurrence of the highest loads occurring in the observed part or structural element during its lifetime.

Verification of security that machinery parts will not fail is accomplished s accomplished by determining the nominal load, that is, the nominal working stress that corresponds to the most frequent stress in the course of operation. The operation conditions, particulary the occurrences of loads higher than normal, are taken into account via the operation conditions factor that is approximately selected from appropriate suggestions. It is easy to conclude that such a method of determining the working stress is approximate, which leads to inadequate dimensions of the structural elements.

High degree of accuracy in dimensioning and reliability verification can be attained by measuring working loads and identifying the load spectrum for vital elements, for example, elements of the transmission gearbox. Spectrum loads are obtained on the basis of operational measurements of the machine system during the operation process for the specified conditions, thus each load spectrum has its probability of occurrence. The selection of a valid spectrum is solved by introducing several representative spectra and determined operation conditions, which enables a sufficiently accurate estimation for all intermediate conditions [3].

2. Working Wheel Transmission Gearbox of the Bucket Wheel Excavator

Bucket wheel excavator is one of the most important machines in the bucket wheel excavator (BWE) system mining operation, and its characteristics are used for the design of other components of the system [7, 8]. The efficiency of the operation of the entire system mostly depends on the operation of the BWE. The form of the BWE design and its dimensions are dependent on the demanded capacity, the method of loading the excavated material and specific conditions of mining such as working terrain stability, material strength and surface load of the soil on which the BWE is placed.

Nowadays, there is a number of various constructions of the BWE that differ in the diameter of a working wheel, number and shape of buckets, position of the transmission for the working wheel drive regarding the boom and the working wheel, etc.

BWEs are mostly manufactured as unique products according to conditions and characteristics of the operating environment in which they are used to mine coal or waste soil (Fig. 1).

Fig. 1 The working wheel of a BWE

The working wheel along with the driving system (electric motor+power transmission) represents a big concentrated mass in a very unfavourable position (the boom top), which is exposed to a constant contact with the excavated mass of soil during operation, thus to loads of a very complex dynamic character.

The driving system (transmission) has a significant influence on the BWE's design because it is directly connected to the working wheel, boom and to the whole construction of the BWE (Fig. 2).

Fig. 2 Toothed gear transmission of BWE's working wheel

Prior knowledge of the stress and the deformation state of the BWE, as well as the dynamic behavior of the transmission in the process of digging would be particularly significant in order to choose the right approach in the BWE design.

Since the process of excavating has a periodical character - the bucket is entering and leaving the soil in cycles - it is impossible to give an exact theoretical definition of the torque on the output shaft in a form of one mathematical function. To provide the exact definition of the torque on the output shaft of the transmission, one should carry out tensiometric measurements of deformations and set grounds for the calculation of the value of torque as a dominant parameter for the calculation of all kinematic parameters of the power transmission (toothed wheel, shafts, bearings, method of connecting shafts and toothed wheels, etc.).

3. Tensiometric Measurements of Torque on Transmission Output Shaft of BWE Srs 1300

Torque can be measured on the gear shaft of the electric motor [4] or on the output shaft of the BWE. In the considered case, torque measurements were carried out on the output shaft of the working wheel gearbox of the bucket wheel excavator SRs 1300 TAKRAF in the coal strip mine Drmno. Measurements were made with a strain gauge set on the transmission output shaft of the working wheel of the BWE.

The basic characteristics of the drivetrain are: power P_M=900 kW, the number of revolutions of the electric motor n_M=1,450 min^{-1}, the transmission ratio i=237.7, the number of revolutions on the output of the working wheel of the BWE- 6.1 to 6.5 min^{-1}.

Torque was measured by employing the principle of measuring mechanical values by electrical means.

The strain gauges were attached to the shaft of the working wheel of the BWE (the output shaft of the gearbox) in a half bridge configuration (Fig. 3). The strain gauges were attached in the main directions of tangential stresses which were caused by the torque on the shaft. The measuring signal was transported by a cable of great length wrapped around the shaft to an amplifier DMC 9012 A and then in the digital form as described to a measuring computer Mc Intosh 520C where it was recorded by the software BEAM ver.3.12.

The momentum caused by mass at distance *l* from the axis of the shaft generated a measuring signal on the measuring stripes that was recorded as a calibration signal in the software and on that basis the measurement of the actual working torque was performed.

Fig. 3 Position of attached measuring stripes on shaft of working wheel

The following devices were used in the experiment:

- measuring stripes LY 12, manufacturer "Hotinger Baldwin Messtechnik"-HBM, Germany
- measuring amplifier DMC 9012A with 6 channels, manufacturer "Hotinger Baldwin Messtechnik"-HBM, Germany
- measuring computer Notebook 520 C, manufacturer Apple McIntosh with software BEAM ver. 3.1, manufacturer "Hotinger Baldwin Messtechnik"-HBM, Germany

Some of the recorded torque values are shown in Figure 4.

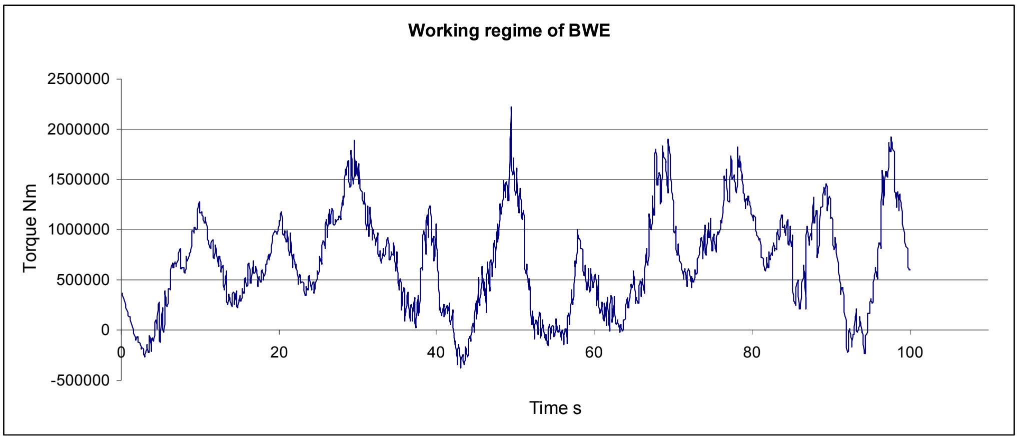

Fig. 4 Recordings of torque measurements on working wheel shaft depending on operating regime of BWE

4. Processing of Measured Values of Torque

The best form to display the characteristics of random processes of the BWE operation and loads such as torque on the working wheel shaft of transmission and stresses for corresponding probability calculations of structural elements of transmission is their discretization and statistical processing in order to gain load spectra [5]. The goal of the statistical processing of the measured values (torque on the output shaft of the BWE transmission) is to create load spectra in the form of distribution functions of certain discrete values, which are characterized by operating loads and stresses. To gain the corresponding load spectra, for the assessment of the stress state in the elements of transmission in the area of time strength of the material experimentally, the following procedure has been followed:

- a parameter is chosen in such a manner that its value will be measured during operation and methods of discretization are chosen as well. The dominant influential factor for the driving transmission of the working wheel of the BWE is the output shaft torque.
- statistical processing of data of the discretized mark is performed and the result is a graphical and analytical description (after the application of the principle of the probability theory and mathematical statistics).

The basic characteristics of the selected random functions are: amplitudes, minimum value, average and maximum values, number and rate of occurrences of certain parameters for a defined period of work, complete number of cycles (of changes) for the exploitation period, etc. This method of discretization isolates the registered marks of the realization of the observed process for statistical processing. These marks are based on a certain hypothesis which derives from a simplified physical display of damage accumulation in the material due to fatigue. They require suitable discretization of random processes for isolating and direct statistical processing large number of changes or cycles of a certain mark at different levels by using classical methods of the mathematical statistics probability theory.

There are a great number of methods for discretization of random processes, which try to substitute the real process of loading or stressing with a simple process in order to more easily isolate and classify the marks. The basic intent is to bring the approximate fatigue process in a material to the real process as close as possible.

Depending on the number of parameters, the methods of discretization can be one-parametric, two-parametric and multi-parametric. For the working wheel transmission, regarding its actual position on the boom, as well as the system of connection with the working wheel, using two-parametric methods would be the best for the discretization of dominant parameters. With these methods, two variables can be classified, for instance, the amplitude and average values (of torque) or maximum upper or minimum lower values.

The originally developed computer program SPECTRUM [6], which, apart from other things, employs the full cycle method, was used to process the broadband change in torque by applying the bi-parametric discretization

total number of extreme values of the process	N_{exv} = 456
maximum value	T_{1max} = 2222900 Nm
minimum value	T_{1min} = -375430 Nm
average value	T_{1sr} = 672200 Nm
number of cross points of medium level T_{1sr} with random process	N_{srv} = 50
coefficient of irregularity	K_{nrg} = 0,1096
minimum amplitude	T_{a1min} = 43 Nm
maximum amplitude	T_{a1max} = 1299200 Nm
lower limit of amplitude	T_{a1d} = 0 Nm
upper limit of amplitude	T_{a1g} = 1300000 Nm
number of amplitude classes	10
width of amplitude class	ΔT_{ai} = 130000 Nm
minimum average value	T_{m1min} = -292970 Nm
maximum average value	T_{m1max} = 1820100 Nm
lower limit of average value	T_{m1d} = -300000 Nm
upper limit of average value	T_{m1g}=1900000 Nm
number of classes of average value	10
width of average class values	ΔT_{mi}=220000 Nm

Table 1 gives the results of the statistical processing of the digital recordings of the measurements, derived by the full cycle discretization.

Table 1 Correlation table of amplitude and average values T_a and T_m

Correlation table		Mean values classes									
		1	2	3	4	5	6	7	8	9	10
Amplitude classes	1	10	21	21	30	33	30	21	12	11	1
	2	0	2	4	7	0	3	1	2	5	0
	3	0	0	0	0	0	1	1	0	1	0
	4	0	0	0	1	1	0	0	0	0	0
	5	0	0	0	0	2	1	0	0	0	0
	6	0	0	0	0	0	0	1	0	0	0
	7	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	1	0	0	0	0
	9	0	0	0	0	0	2	0	0	0	0
	10	0	0	0	0	0	1	0	0	0	0

Table 2 Processing results 6th class, mean values T_{m6}=800000-1020000 Nm)

Class	T_{ai} / Nm	n_i	n_{uki}	$f_i = \frac{n_i}{n_{uk}}$	F_i	H_i	$H_i \cdot n_b$	$\log(H_i \cdot n_b)$
1	0-130000	30	30	0,7692	0,7692	0,2308	230800	5,3632
2	130000-260000	3	33	0,0769	0,8462	0,1538	153800	5,1871
3	260000-390000	1	34	0,0256	0,8718	0,1282	128200	5,1079
4	390000-520000	0	34	0	0,8718	0,1282	128200	5,1079
5	520000-650000	1	35	0,0256	0,8974	0,1026	102600	5,0110
6	650000-780000	0	35	0	0,8974	0,1026	102600	5,0110
7	780000-910000	0	35	0	0,8974	0,1026	102600	5,0110
8	910000-1040000	1	36	0,0256	0,9231	0,0769	76900	4,8861
9	1040000-1170000	2	38	0,0513	0,9744	0,0256	25600	4,4089
10	1170000-1300000	1	39	0,0256	1,0000	0	0	-

In Figure 5 the stereogram extracted from the correlation table is shown.

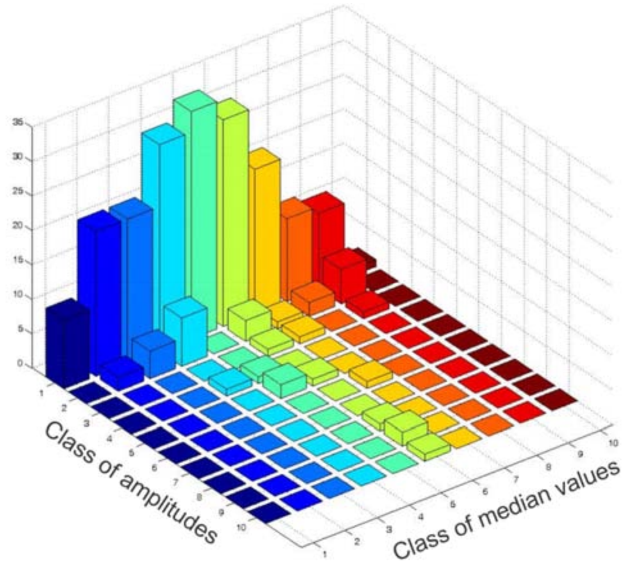

Fig. 5 Stereogram obtained from correlation table

The statistical processing of the discretized mark data histogram of the amplitude distribution density (Fig. 6), cumulative increasing distribution F(x) (Fig. 7), cumulative decreasing distribution H(x) (Fig. 8), and, finally, the spectrum of load per unit (Fig. 9) follow.

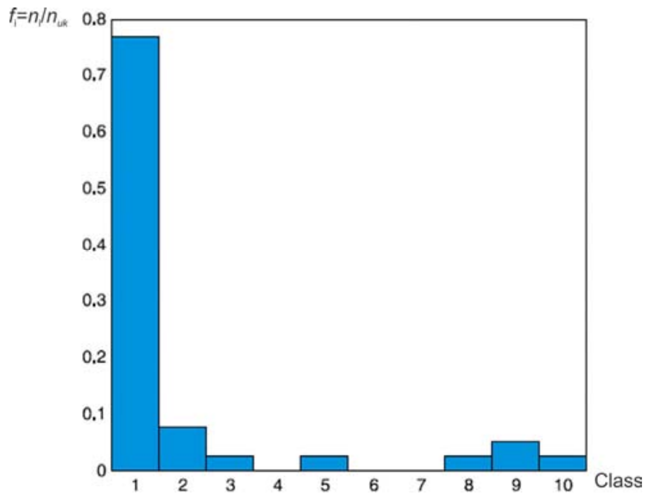

Fig. 6 Amplitude distribution density histogram f(T_a) 6th class mean value T_{m6}=800000 – 1020000 Nm

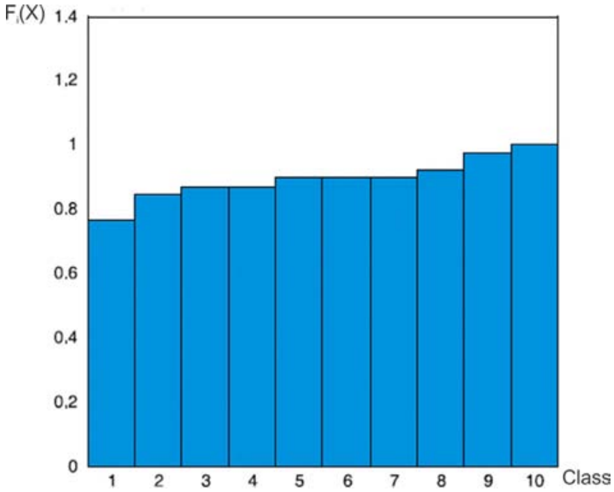

Fig. 7 Cumulative increasing distribution F(x)

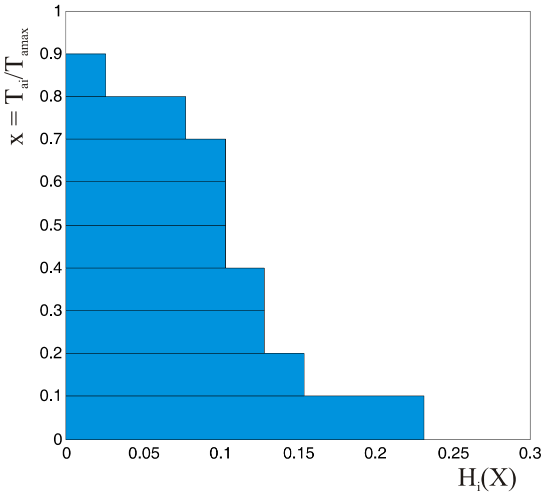

Fig. 8 Cumulative decreasing distribution H(x)

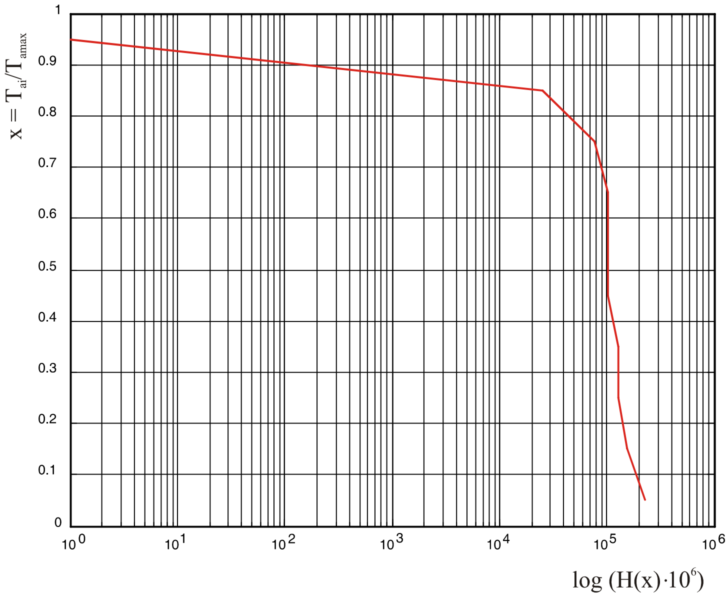

Fig. 9 Unit spectrum of amplitudes $H(x)\cdot 10^6$ in logarithmic scale

In comparison with characteristic representatives of the operating regime, we can conclude that this spectrum belongs to the heavy operating regime.

Table 3 Processing results

Class	T_{ai} / Nm	n_i	n_{uki}	T_{ai} / Nm	$N(T_{ai})$	$F(T_{ai})=MR$, %
1	0-130000	30	30	130000	30	75,42
2	130000-260000	3	33	260000	33	83,044
3	260000-390000	1	34	520000	34	85,585
4	390000-520000	0	34			
5	520000-650000	1	35	910000	35	88,126
6	650000-780000	0	35			
7	780000-910000	0	35			
8	910000-1040000	1	36	1040000	36	90,665
9	1040000-1170000	2	38	1170000	38	95,734
10	1170000-1300000	1	39	1300000	39	98,238

Empiric values of the cumulative distribution function $F(T_{ai})$ can be represented by the Weibull distribution. Parameters of this distribution are the shape parameter β and the scale parameter η and the simplest method for their determination is the probability plot method within Weibull probability paper [12].

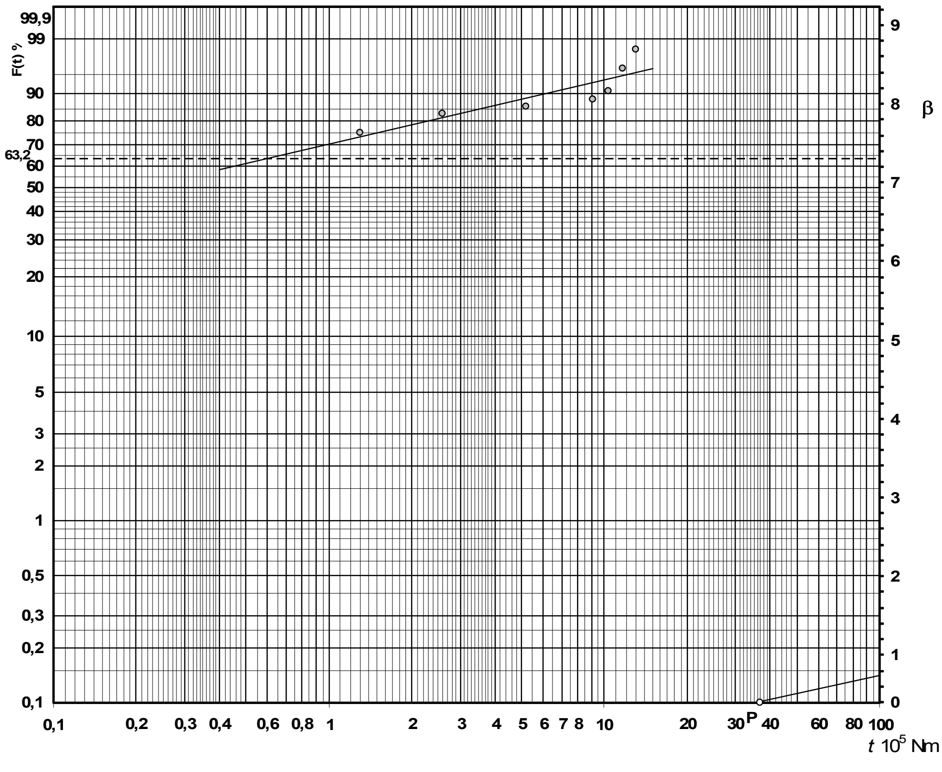

Fig. 10 Torque distribution amplitude

Figure 10 implies that the given empiric data is not homogenous and it is not possible to draw a straight line between the dots. Furthermore, it implies that the distribution might be a complex Weibull distribution. It is possible to draw two lines that will group specific dots (the first set of 3 dots groups around the first line and the second set of 4 dots groups around the second line). After this grouping, these empirical data are considered as two samples/examples (Tables 4 and 5).

Table 4 Processing results of first sample

Class	T_{ai} / Nm	n_i	n_{uki}	T_{ai} / Nm	$N(T_{ai})$	$F(T_{ai})=MR$, %
1	0-130000	30	30	130000	30	86,397
2	130000-260000	3	33	260000	33	95,113
3	260000-390000	1	34	520000	34	97,982

Table 5 Processing results of second sample

Class	T_{ai} / Nm	n_i	n_{uki}	T_{ai} / Nm	$N(T_{ai})$	$F(T_{ai})=MR$, %
1	520000-650000	1	1	910000	1	12,945
	650000-780000	0	1			
	780000-910000	0	1			
2	910000-1040000	1	2	1040000	2	31,381
3	1040000-1170000	2	4	1170000	4	68,619
4	1170000-1300000	1	5	1300000	5	87,055

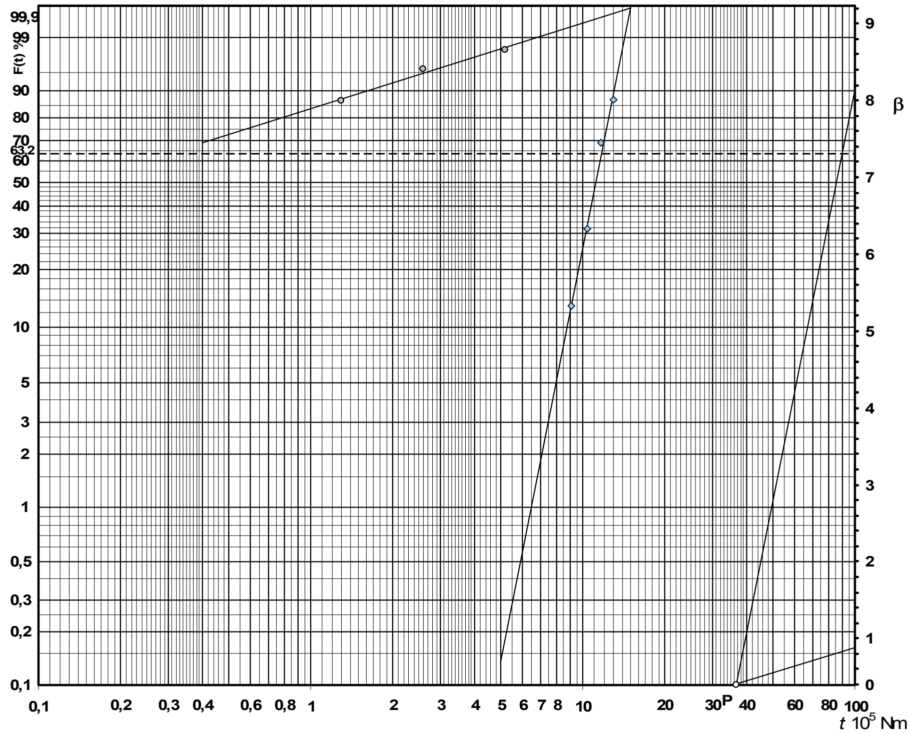

Fig. 11 Complex Weibull torque distribution of amplitude

Parameters of the Weibull distribution of the first sample are: $\beta = 0.4842$ and $\eta = 29{,}748$ Nm. Parameters of the Weibull distribution of the second sample are: $\beta = 7.75$ and $\eta = 1{,}171{,}642$ Nm. Dominant data, i.e. the data that influence operating regimes, are from the second sample of data.

The torque amplitude probability distribution is:

$$F\left(T_{am}\right) = 1 - e^{-\left(\frac{T_{am}}{1171642}\right)^{7,75}} \tag{1}$$

The amplitude of the torque with the highest density distribution is:

$$T_{am} = \eta \cdot \sqrt[\beta]{\frac{\beta - 1}{\beta}} = 1171642 \cdot \sqrt[7.75]{\frac{7.75 - 1}{7.75}} = 1150946{,}67 \text{ Nm} \tag{2}$$

Decision about the operating condition results from the ratio of the amplitude of the torque with the highest density and maximal amplitude of the torque.

$$x_m = \frac{T_{am}}{T_{a\max}} = \frac{1150946,67}{1300000} = 0,885 \qquad (3)$$

The value x_m=0,885 results in a conclusion that the spectrum of loads is heavy.

The authoritative load spectrum for the calculation of vital elements of the bucket excavator working wheel transmission is given in Fig. 12 for the example of the bucket wheel excavator at the Drmno barren soil excavation site. According to DIN 45667, this spectrum would correspond to heavy work regime.

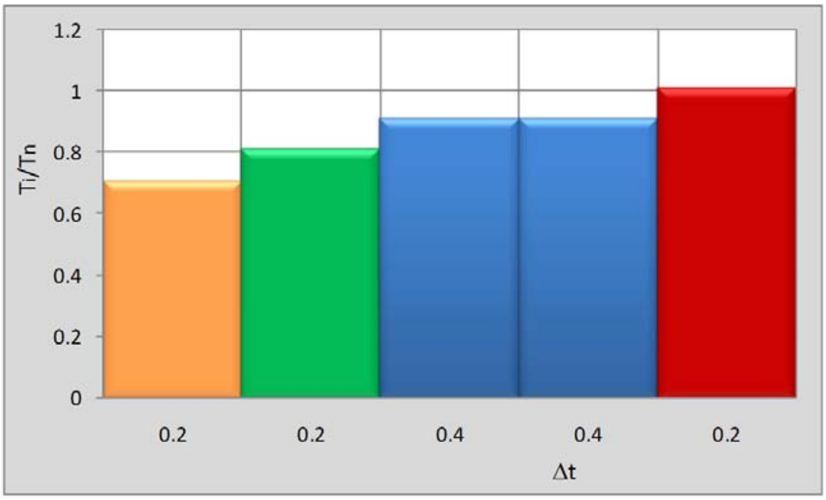

Fig. 12 Authoritative load spectrum

5. Conclusions

On the basis of the previous considerations, the conclusions are as follows:

- Bucket wheel excavators are highly complex mining machines used in coal strip mines, whose safe and reliable operation affects the country's energy supply,
- An adequate calculation of vital parts of the excavator driving mechanisms provides basic preconditions for their more efficient operation, which are realized during exploitation,
- Design of a toothed gear power transmission as a complex mechanical system is a very complex designing and structural task which requires the application of contemporary designing methods.
- High degree of accuracy for the design of the elements of the toothed gear power transmission can be achieved by simulating operating conditions by means of the calculation with defined load spectra.
- In order to obtain the load spectrum as a basis for the design of gearbox power transmission elements of the working wheel of a BWE, the tensiometric measurements of torque (being a dominant parameter) were carried out on the output shaft of the gearbox of the working wheel of the BWE SRs 1300 TAKRAF in the open pit excavation operation in Drmno,
- On the basis of the measurements, by discretaization via the full cycle method, a spectrum load was defined which can be used in the design of structural components of the power transmission of the working wheel of the BWE operating at Drmno.
- Experimental measurements of this type have to be done on BWEs operating in real conditions, otherwise the results of the calculations/design give non-realistic results.

- Based on the conducted tensiometric measurements by discretization via the method of full cycles, the authoritative load spectrum is defined for the calculation of vital elements of the drive system in an analytical and graphical form.
- The obtained load spectrum corresponds to heavy work regime.

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