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Theoretical and Experimental Fatigue Analysis for the MU450 Top Drive Drilling Mast

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Abstract

Due to the working conditions, to the loads that are dynamic, and repetitive, the fatigue is an important issue in the case of the drilling masts. The authors devised the following approach: perform an experimental analysis on a scale model of a drilling mast, with the aim to obtain the damping coefficients associated with the vibration modes of the model; extrapolate the results on a real model using the similarity theory; use the results of the previous step to obtain the Frequency response function of the mast; perform a fatigue finite elements analysis for the mast; assess the impact of the mounting / manufacturing errors on the reliability of the mast.

Key words: *program drilling rigs, reliability, hoisting system*

Introduction

Taking into account that the dynamic character of the loads applied to a drilling mast is of great importance, in the sense that it will augment the values of the beam stresses, the authors propose the following approach, in order to make an assessment of the mast reliability: using a scale model of a mast, one determines the first five natural frequencies; for the scale model, the same first five natural frequencies are determined, using the Finite Element Method, in order to verify the experimental values; using the experimental values (the response curves, analyzed with the software produced by Bruel-Kjaer), one determines the damping ratios, for each mode; using the similarity theory, the values were extrapolated to the real mast; for the real mast, a Finite Element Method analysis has been performed, in order to calculate the beam stresses due to dynamic loads; mast lifetime was evaluated using criterion Palmgren - Miner of linear damages accumulation; perform the reliability analysis, using the Monte Carlo method and neuronal networks.

Mast Analysis

General aspects

The drill rigs, particularly the hoisting system of these facilities are very complicated elastic systems. The safely operation of these facilities depends largely on their dynamic behaviour. This is explained by the dynamic stresses of vibration and transient regimes that are added to the static loads, exceeding the strength of those elements considered in the design [3].In these circumstances the hook force of the drilling rig has a more complicated expression. It depends on the activity carried out within the plant. The team of researchers from the Department of Mechanical Engineering of UPG Ploiesti conducted numerous works on these influences [1]. Thus for the drilling string lifting from wedges it has proposed the formula of the hook force [2]:

$$F_{cd} = F_{cs} A \sin(\omega_0 t + \varphi_0) + F_{cs} e^{-mt}(at + b) + F \sin(\omega_0 t) \tag{1}$$

where: F_c is the hook force expressed in dynamic regime, F_{cs} hook force expressed at steady regime, F disturbing force, $\omega_1$frequency entered into the hoisting system, ω_0 natural frequency of the hoisting system, φ_0 phase angle due to the inertia of the system, and A, m, a, b are coefficients which depend on the characteristics of the hoisting system. It was defined a dynamic coefficient [2], the ratio of the dynamic and steady force:

$$K_d = \frac{F_{cd}}{F_{cs}} F_{cd} \tag{2}$$

For dynamic coefficient they found different expressions that take into account: the elasticity of the hoisting system, the characteristic of the actuating groups, the influence of hydraulic transmission, the influence of the degree of acceleration of the engines, the flexibility and elasticity influence of the operational couplings. Also, because of the complexity of the problem it has been sought to simplify these expressions, finding only the value of the maximum dynamic coefficient. Generally these values are high, ranging between 1.5 and 2. The experimental determinations are critical in the establishing of the dynamic coefficient and the variation of the hook force obtained under these conditions is an important element in the design. Figure 1 presents the hook force variation recorded for the drilling rig 4DH-315. There are high values of dynamic coefficient, which justifies the above considerations.

The modern programs can take the force variation (experimentally obtained) and in a dynamic study can be seen the efforts generated into the mast structure. Into the achievement of a model in dynamic regime, the determination of the natural frequencies of the mast structure is indispensable. Further it is chosen a number of the natural frequencies and using the model of the variation of hook force (s. next) are determined the stresses corresponding to the dynamic regime. Unfortunately the authors do not have records on the hook force variation for mast analysed. The calculus of the natural frequencies described in detail in section 2.2-2.4, is a necessary element in solving the problem. We take account of the variation of hook force (qualitatively) in the fatigue calculation.

Table 1. The experimental and calculated natural frequencies

Nr. Frequency	**Frequencies [Hz]**	
	Calculated (FEM)	**Experimental**
1	8.57	8.8
2	11.70	11.6
3	25.90	24.4
4	42.20	49.6
5	57.00	56.4

Experimental work

The scale model and the gear used are presented in Figure 2. One used a Bruel-Kjaer vibration analyser, with an accelerometer type gauge (4370). The structure has been excited with an impact hammer. The response covered the 0-1000 Hz range. The experiment produced the frequency response curves as a module of the Fourier transform. Figure 3 presents one of these curves. After processing the curves, the first five natural frequencies were obtained. For the scale model, the same values were determined. The two sets of values are presented in Table 1.

The approach was to neglect the reciprocal influence each vibration mode has aver the other ones (one degree of freedom model). Using the methodology presented in [5], and analysing figure 4, the following relations were used (the results are presented in Table 2):

$$\eta_r = \frac{(\omega_a^2 - \omega_b^2)}{\omega_r^2} \tag{3}$$

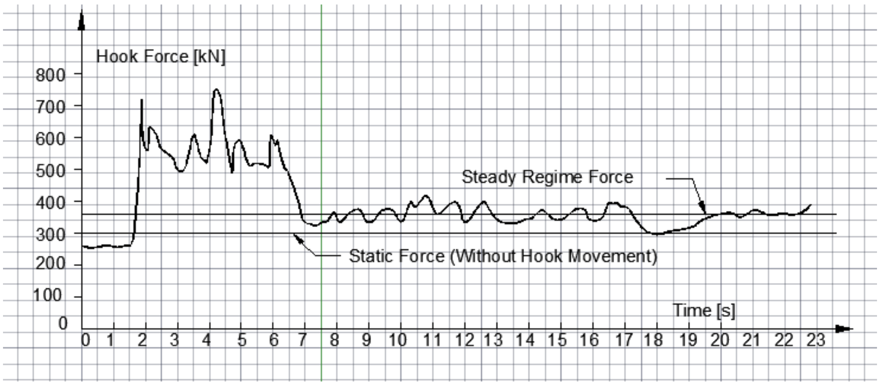


Fig. 1. Variation of the hook force for the drilling string lifting from wedges [2].

Table 2. The natural frequencies for the real structure

Nr. Freq.	**W_r [Hz]**	**W_a [Hz]**	**W_b [Hz]**	**η_r [-]**	**ζ_r [-]**
1	8.8	8.972	8.591	0.086	0.173
2	11.6	11.800	11.400	0.069	0.138
3	25.4	24.800	24.300	0.041	0.082
4	49.6	49.750	49.340	0.017	0.033
5	56.4	56.560	56.230	0.012	0.023

Extrapolating the results on the real model using the similarity theory

Using the π [8] theorem to the implicit function:

$$f(\sigma, F, g, l, E, \delta, k, t) = 0 \tag{4}$$

we reach the following criteria:

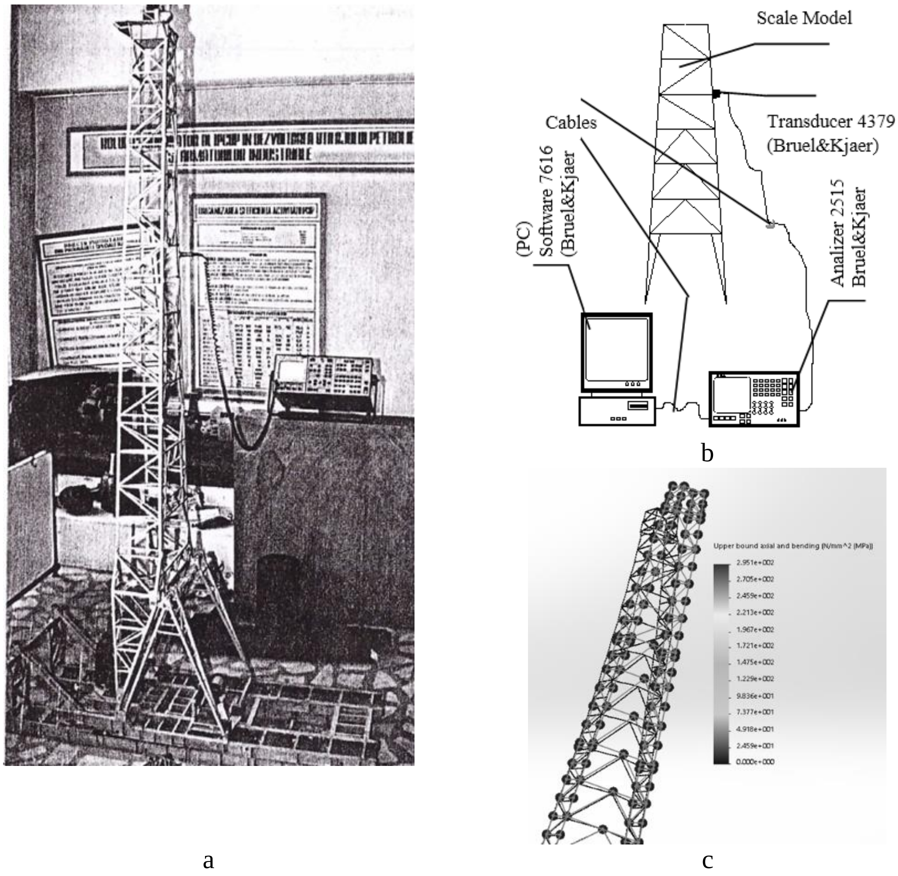
$$\pi_1 = \frac{l\sigma^{\frac{1}{2}}}{F^{\frac{1}{2}}};\ \pi_2 = \frac{\sigma}{E};\ \pi_3 = \frac{\delta\sigma^{\frac{1}{2}}}{F^{\frac{1}{2}}};\quad \pi_4 = \frac{k}{\sqrt{\sigma F}};\ \pi_5 = \frac{\sigma^{\frac{1}{4}} g^{\frac{1}{2}} t}{F^{\frac{1}{4}}}\ \text{or} \tag{5}$$

$$\pi_1 = \frac{F}{\sigma l^2};\ \pi_2 = \frac{E}{\sigma};\ \pi_3 = \frac{\delta}{l};\quad \pi_4 = \frac{k}{\sqrt{\sigma F}};\ \pi_5 = \frac{g\,t^2}{l} \tag{6}$$

where the notations are easy to understand: σ – stress, δ – displacement, E – elasticity modulus, F – force, l – dimensions, k – stiffness, g – acceleration of gravity, t – time. The criterial equation will be:

$$\varphi\left(\frac{F}{\sigma l^2}, \frac{E}{\sigma}, \frac{\delta}{l}, \frac{k}{\sqrt{\sigma F}}, \frac{g\,t^2}{l}\right)\ \text{or} \tag{7}$$

$$\varphi\left(\frac{F}{\sigma l^2}, \frac{E\delta}{\sigma l}, \frac{k}{\sqrt{\sigma F}}, \frac{g\,t^2}{l}\right) \tag{8}$$



b

a c

Fig. 2. The experimental scheme: a) mast model; b) experimental chain; c) numerical simulation.

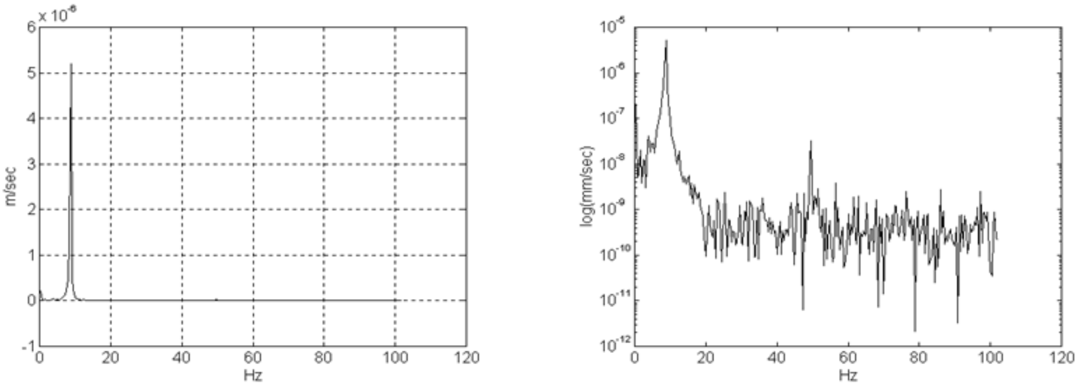


Fig. 3. Frequency Response Curve.

Table 3. Drilling program

Drilling depth, [m]	**Maximum hook force,** [kN]	**Number of the drilling bits,** [–]	**Drilling velocity, [**m/h]	**Lifetime of the drilling bit,** [h]	**Number of cycles,** [–]	**Remaining life of the drilling rig,** [%]
1500	856	7	7	30	224	100
4000	1630	47	2,5	21	3753	99.97
8000	2393	222	1	18	36759	97

The proportionality laws we get to, are:

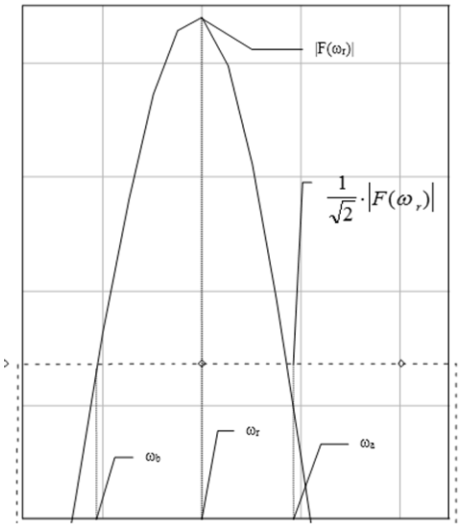


Fig. 4. Plot analysis for determining the modal parameters.

$$\frac{K_F}{K_\sigma \lambda^2}=1;\ \frac{K_E\, K_\delta}{\lambda\, K_\sigma}=1;\ \frac{K_k}{\sqrt{K_\sigma K_F}}=1;\ \frac{K_g\, \tau^2}{\lambda}=1 \tag{9}$$

$$K_F=\frac{F_{\text{prototip}}}{F_{\text{model}}} \tag{10}$$

$$\lambda=\frac{l_{\text{prototip}}}{l_{\text{model}}} \tag{11}$$

where K_F, K_E an so on are the scales for the corresponding quantities. For example: force and the lengths scale. Processing the results and the above equations, we get to the natural frequencies for the real structure: 1.44; 8.95; 24.82; 48.13; 78.69 [Hz]. The modal parameters obtained by corresponding the vibration modes of the scale model and real model, are: $\zeta_1=0.17;\zeta_2=0.15;\zeta_3=0.15\zeta_4=0.14;\zeta_5=0.15$.

Fatigue Calculus of the Mast

For the fatigue calculation it is considered the drilling program, Table 3, conducted with drill pipe 5 ½ "(outside diameter OD = 139.7 mm and weight per meter q = 328 N / m).The average speeds used for drilling and the average lifetime of a drilling bit are indicated in the Table 3, calculating the number of the bits of on each drilling interval with the formula:

$$n_s=\frac{L_s}{v_s \cdot h_s} \tag{12}$$

where: n_s – number of drilling bits, L_s – drilling depth, v_s – drilling velocity, h_s – lifetime of the drilling bit. For example it was considered a material used in the construction of the mast S355 JR which has the fatigue test characteristic curve shown in the Figure 5. For each drilling interval (e.g., between 0 and 1500 m, figure 6) comes out a number of the bit replacements. A specific bit replacement is characterized by the hook force in the moment of an unacceptable wear of the drill bit, and the depth of drilling when this event occurs. At this point, begins the handling the drill string extraction - replacement -introduction, characterized by the variable forces obtained by changing the length of the drill string, Figure 7. From Figure 7 (example, the failure of the bit at the depth of 643 m, hook load 397 kN) one observes that there are a total of 25 cycles of extraction / insertion of the drilling string, corresponding to this replacement. The stresses into the mast structure are variable, being determined by the corresponding forces to the hook. Knowing the hook force at a specific time (a certain length of the drilling string into the maneuver) is determined by using the program Cosmos maximum stress into the mast structure.

Further from the fatigue diagram Figure 5, the maximum number of cycles corresponding to a certain situation is set. Formula that estimates the lifetime of the mast is:

$$\sum_{i=1}^{nc}\frac{n_i}{N_i}=1 \tag{13}$$

where: n_c is the number of load cases corresponding to different forces at the hook; n_i is the number of cycles corresponding to the maximum number of cycles N_i (that is completely deplete the lifetime of the material at a stress σ_i). In each distinct loading case are performed the following steps:

a. The static hook force for a specific length of the drilling string is determined (at the depth of the hole, when the drilling bit fails;

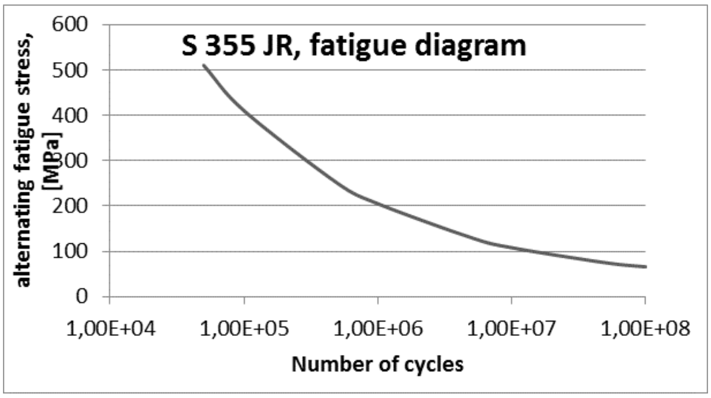


Fig. 5. Curve S (stress) - N (number of cycles) of fatigue durability S 355 JR material. (E=210000 MPa, G=80800MPa, μ=0.3 (Poisson), ρ=7850 kg/m^3, SYS=355 MPa, SUTS=510 MPa).

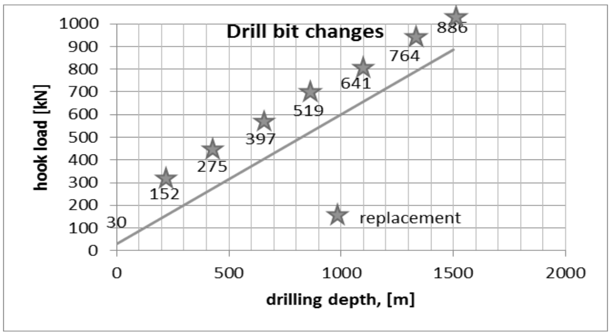


Fig. 6. The maximum hook forces at the replacement of the bit, corresponding to the drilling interval 0-1500 m.

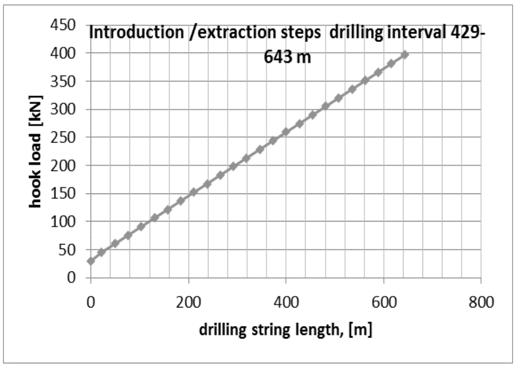


Fig. 7. The variation of hook force during the extraction/introduction of the drilling string at the depth of 643 m.

b. It is generated the diagram of the hook force variation, Figure 8,*c*; the model for this variation is expressed into the Figure 4;

c. It is established the maximum value of the stress in mast structure with Cosmos program σ_i ;

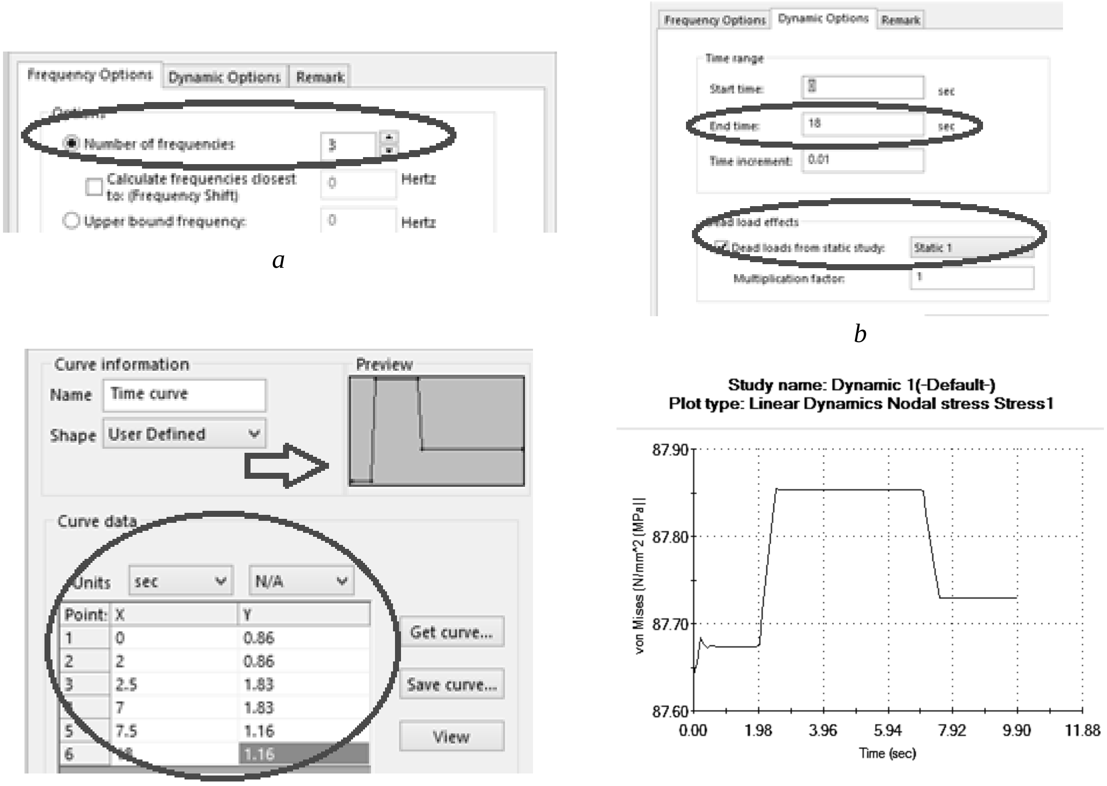
d. It is selected the maximum number of cycles N_i at the maximum stress, from Figure 5;

e. They are considered two cycles (extraction/insertion) that are divided by the value of N_i;

f. It is subtracted this report 2 / N_i from lifetime (which is initially 1); thus constantly is updated the remaining lifetime;

g. By the removing of a step of the drilling string (3 parts) its length is shorter with the length of this step;

h. It repeats the calculations from the paragraphs a-g until the drill string length is equal to zero. In this way we can evaluate (at a specific drilling program) the percent of the exhausted lifetime of the mast and it can be estimated the reserve of capacity corresponding to the fatigue solicitations over the time. The calculation is based on statistical parameters of drilling: the value of cutting speed and duration of use of the bit, which are known at the end of a drilling program. The fatigue assessment was conducted in a Matlab program, which uses information provided by the program Cosmos that analyzes the structure of the mast. The number of cycles corresponding to each interval of drilling and remaining lifetime are given in the last two columns of Table 3.



Options

● Number of frequencies: 3

☐ Calculate frequencies closest to: (Frequency Shift) 0 Hertz

○ Upper bound frequency: 0 Hertz

a

Time range

Start time: 0 sec

End time: 18 sec

Time increment: 0.01

Dead load effects

☑ Dead loads from static study: Static 1

Multiplication factor: 1

b

Name: Time curve

Shape: User Defined

Units: sec N/A

Point:	X	Y
1	0	0.86
2	2	0.86
3	2.5	1.83
[illegible]	7	1.83
5	7.5	1.16
6	[illegible]	1.16

c *d*

Fig. 8. The data used in a linear dynamic study: a) the number of natural frequencies considered; b) the length of time allocated to the study; c) the definition of the load diagram - static hook force multiplier at different times; d) the time evolution of the stresses in a node of the structure

Reliability Calculus of the Drilling Mast

To calculate the mast reliability, we focused on the following variables: mounting errors translated into variations of the geometric elements making up the mast sections; manufacturing errors in the profiles of the mast; loading force of the mast; the characteristics of the materials used at the construction of the metal structures. All these influences determines a state of stresses in the mast analysed. Appreciation of mast failure can be done by the difference between the selected ultimate tensile strength *SUTS* and maximum structure stress T_m:

$$Z = SUTS - T_m \tag{14}$$

To assess the limit state $Z = 0$, we proceeded as follows:

a. They were defined the geometric elements defining a section of the mast construction, Figure 9. Compared with the imposed values these six geometrical dimensions may vary by possible errors of construction / assembly. To these elements L, l, a, b, c, d, we added three parameters which characterize the metal profiles used in the construction of the section of the mast parts p, q, r. There are three different types of profiles for a section, and each of these have been characterized solely by a geometric parameters (p, q and r) in order to simplify the evaluation. The last three variables may change depending on the execution of these profiles.

b. The mast structure analyzed is formed from the metal crown block, three sections similar to the one shown in the Figure 4 and the fixing base part of the mast. A total of five distinct sub-assemblies. For each of these the characterization by the nine parameters (described above) is maintained. Each parameter is numbered with an index i = 1-5 corresponding to the sub-assembly in which it is included.

c. For a certain section it was considered a normal variation of the value of geometrical parameters exemplified for the section 2 of Figure 9, Table 4, adding the maximum hook load variation. The modification of the hook force combined with mounting and manufacturing errors characterizes a state of stresses in the mast, from which it retains only maximum stress. In total in this variant (simplified) the distribution of the stresses into mast depends of 46 variables:

$$T_m = T_m(L_i, l_i, a_i, b_i, c_i, d_i, p_i, q_i, r_i, F), i = 1..5 \qquad (15)$$

d. With a set of variables is generated the mast structure and it determines the maximum stress of it.

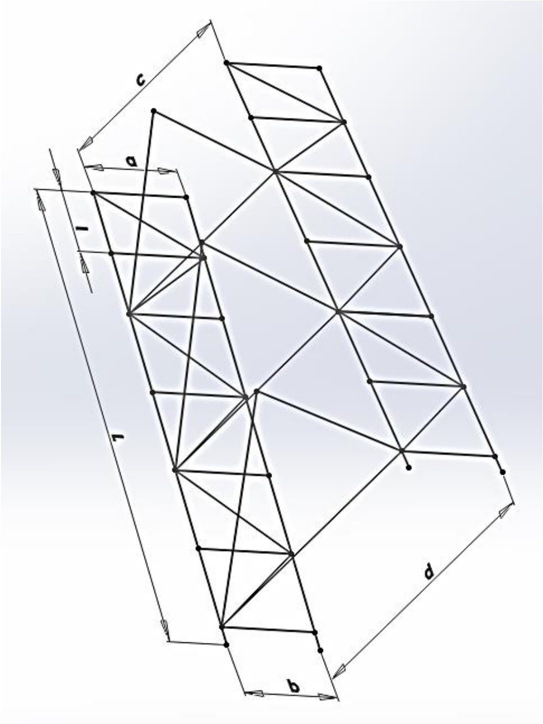


Fig. 9. Geometric elements that have been used to define a section of the mast construction.

e. Further considering also a probabilistic variation for *SUTS* with average 510 MPa and standard deviation of 30 MPa, the limit state can be evaluated as described by equation (14).

f. To calculate the failure probability *PF* of the mast, the Monte Carlo method is used. If the difference expressed by equation (14) is positive, situation is favorable and the structure does not fail. If the difference is less than or equal to zero, the structure fail. We note that the number of attempts at which $Z \leq 0$ with n_d. Failure probability expressed for a number of tests *N* carried out in application of the Monte Carlo method is:

$$PF = \frac{n_d}{N} \qquad (16)$$

Since the generation of a structure from each set of probabilistic variables and analysis mast is a laborious technique, it was worked with neural networks.

g. The neural network method, theoretically developed in the middle of the twentieth century, began to be used frequently in last fifteen years because computing progress. Special applications concerning oil fields identification, indication of extraction pumps defects, welding robots work coordination, analyzing high risk elements from petrochemical plants, etc. are made actually by this technique. Matlab and Neural Network Toolbox specialized modulus permit the designing of some kind of applications simplifying the mathematic aspect and coming rapidly on problem solution.

h. This technique involves the construction of neural network, adapted to find a model of a given problem. In our case we have the set the input variables (46 variables) and of the maximum stress (from the mast structure – output value) provided by Cosmos program. We wish the model of the analyzed system (the drilling mast). The model (neural network) must correctly anticipate the results (maximum stress) to a particular set of input variables. The model elements (neurons) are determined in a learning process, using a set of input data and knowing the answers (maximum stress from Cosmos program).

i. Such were generated 30 sets of input data together with the maximum stress of the structure obtained by the running of the program Cosmos, equation (15). Getting these different models and the results implies a considerable time.

Table 4. The set of variables

Random variable and measuring unit	**Meaning**	**Average, [m]**	**Standard deviation, [m]**
L, [m]	Part length	11.40	0.05
l, [m]	Distance between weld point	1.9	0.03
a, [m]	Upper lateral part width	2.7	0.04
b, [m]	Lower lateral part width	2.7	0.04
c, [m]	Upper central part width	5.4	0.04
d, [m]	Lower lateral part width	7.4	0.050
p, [m]	Beam profile vertical dimension	0.24	0.012
q, [m]	Beam profile vertical dimension	0.20	0.011
r, [m]	Beam profile vertical dimension	0.22	0.011
F, [kN]	Hook load	5 000	150

j. The application of Monte Carlo method requires a large number of tests and is not possible to make a large number of tests on a three-dimensional model of the mast, built each time.

k. These 30 data sets were used for the construction (learning) of the neural network, in order to obtain a rapid response to a set of input probabilistic variables. The network used is given in Figure 10, the radial type with two layers: first with 30 neurons and hidden layer with one neuron.

l. In these conditions using the Monte Carlo method becomes effective, may test the condition (14) and evaluate the probability of failure (16) for a large number of trials. The reliability of assessed mast it is determined by the distorted structure generated by the mounting / execution errors and *SUTS* variation is 0.9687. This means that in 3 % of cases mast can fail due to the deviations mentioned.

Conclusions

The paper proposes an integrated approach in analyzing a mast behavior due to dynamic loading, making use of different tools, starting with experimental measurements, then passing through the Finite Element Method, the Monte Carlo method and neuronal networks. The results allow the authors to make assumptions on the mast reliability, a problem of great interest in the case of these structures. The main contributions to the paper are the following. It determines (experimental) the natural frequencies of the structure and it extrapolates these results using similarity theory. It performs a tridimensional model of the mast and it applies the finite element method to determine the state of tension. A linear dynamic study is used to capture the tension variation in agreement with the variation of hook force on the maneuver; this study is based on the natural frequencies of the structure. A fatigue calculation of the mast is made assuming the variation of tensions in its structure during the maneuver; the damage calculation, for the variable loads consisting of cycles with different amplitudes, is based on the adopted criterion Palmgren - Miner of linear damages accumulation.

To calculate the lifetime of the mast structure were determined: number of cycles n_1, n_2, ..., n_k for each maximum stress in the structure σ_1, σ_2, ..., σ_k, based on the sequence of loading in operating conditions of the analyzed structure. The number of cycles to failure N_1, N_2, ..., N_k, for constant amplitude fatigue testing (corresponding to the stress amplitudes σ_1, σ_2, ..., σ_k) are based on curve *S* (stress) - *N* (number of cycles) of fatigue durability (S 355 JR material). The method is a measure of the mast wear, like that used to quantify the wear of the drilling cable by cumulative mechanical work procedure. It determines the influence of errors of construction /

installation on the mast reliability. For this, its geometry is characterized by 45 statistical variables with a normal distribution, plus the tensile strength of the material (it is also considered as statistical variables with a normal distribution). Mast models for 30 sets of values are used to obtain the maximum stress in the structure.It is built a neural network equivalent with the structure model which is used to determine the reliability by Monte Carlo method. In exemplified drilling program there is a probability of 3 % failure due to causes mentioned.

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Analiza teoretică și experimentală a mastului MU 450 al instalației de foraj cu acționare la partea superioară

Rezumat

Datorită condițiilor de lucru, cu sarcini dinamice și repetitive, oboseala este un o problemă importantă în cazul masturilor de foraj. Autorii au structurat problema enunțată în titlu astfel: au efectuat o analiză experimentală pe un model la scară al unui mast de foraj cu scopul de a obține coeficienții de amortizare asociați modurilor proprii de vibrații ale modelului; au extrapolat rezultatele pe un model real folosind teoria similitudinii; au utilizat rezultatele din pașii anteriori pentru a obține funcția de răspuns în frecvență a mastului; au efectuat o analiză cu element finit a mastului; au apreciat impactul erorilor de montaj și de execuție asupra fiabilității mastului de foraj.

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