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Study of the Behaviour of a Transportable Mast of 500 kN Maximum Hook Load during Free Vibrations

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Abstract

Drilling, followed or interrupted sometimes by interventions or overhauling activities, is one of the most costly and full of the possibility of danger or failure activity. Failure of one of rig components, and in particular the mast, can lead to very big and unwanted cost implications. The question of masts vibrations is a concern for drillers and, also, for design engineers during the rigs functioning in oil fields. It is obvious that, for a given construction of a mast, is necessary to know in advance its natural frequencies values, in order to avoid them during rig's work. In this paper it is analyzed the dynamic behaviour of a transportable mast of 500 kN maximum hook load, in the case of the free vibrations. The mast is made out of three sections: a fix, an inferior and a superior section, composing a complex spatial structure, statically undetermined. In its assembly, the mast is made out of straight beams with different cross-sections, being linked to truck chassis by the means of four strength anchors: two, fixed at the crown block's level and two at the top of the inferior part. Authors used the Finite Elements Analysis with the aim to determine the first ten natural frequencies and the correspondent mode shapes for the first five. The evaluation of all factors which can produce forced vibrations during rig's functioning and the risks of the appearance of resonance phenomenon are pointed out.

Key words: *transportable mast, free vibration, frequency, shape mode, FEA.*

Constructive Analysis of the Mast

The mast of 500 kN maximum hook load is an important component of the AM 12/50 transportable workover rig used for interventions and overhauling works for oil and gas wells. It is composed of three sections [6], [8]: fixed section, the lower one and the upper one. During their transportation to the rig site, they are laid into a horizontal position on a special truck chassis (fig. 1), with the upper section introduced in the interior of the lower one. Before starting the work, the upper section is extracted (by telescoping) from the interior of the lower section, then fixed to this one, both of them being then brought as an assembly into a quasi-inclined position against a vertical axis (5.3°) due to their connection between the inferior zone of the lower section and the superior zone of the fixed section, as it is shown in Figure 2. The final total height of the mast is 21 m.

There are in mast's composition bars with cross-section made of various profiles: L, I, U and rectangular structural hollow, and in the cross-section of the assembly the mast is U-shaped. The rated or working hook load was deemed in calculation to have the value Q =375 kN [8] and the loading for the overload test was evaluated to the value $Q_p = 1.4 \cdot Q_{\max} = 700\,kN$ [6], where Q_{max} = 500 kN is the maximum hook load for the workover rig of the mast subjected to the proposed analysis. Calculations were done in the absence of safety anchors, considering the mast connected to the ground only by means of the four strength anchors (fig. 2).

Fig. 1. Workover rig [12]

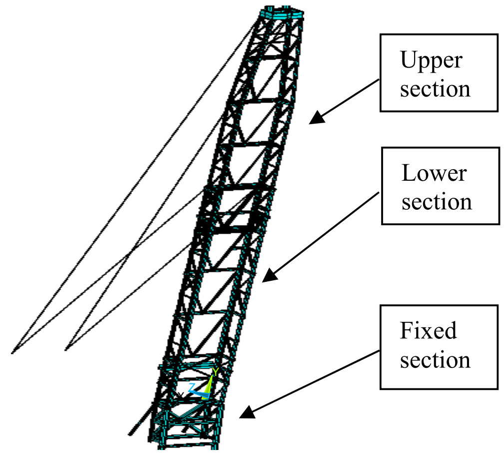

Fig. 2. Assembly view of mast

The fixed section is composed of two pillars made of pipe Ø168.3x16, steel S235, placed in the front side of the structure and of other two pillars made of profile "L120x120x12, steel S355J2, SR EN 10025-2 (left and right), placed on the back side of such, and also diagonal, lateral and transversal bars made of profile L120x120x12. On the back side there are provided two counterbraces that have at the lower extremity catch forks placed 1,000 mm distance away from the back side of it. The upper plane of the fixed section is quasi-inclined to an angle against horizontal plane of 5.3°, which assures a slight inclination against the vertical axis for the entire assembly during work in the wellhead" [6], [8].

The lower section is composed of four identical pillars, having the cross-section made of profile L120x120x12. "There are in its composition: 7 horizontal bars and 14 lateral bars made of rectangular pipe 100x60x6, same steel, 42 diagonal bars made of L60x60x6 onto all the three faces of the section, a horizontal bar made of profile HE 200 M placed at the lower side of the section, on the second panel" [8].

The upper section is composed of four pillars made of profile L100x100x10. These pillars cover "six panels composed of horizontal and diagonal bars, over the length of the first three being parallel between each other, having a prism design, and on the last three panels being disposed upon directions inclined against the local vertical axis of the pillar, with appearance of truncated pyramid design. There can be met also: 5 horizontal bars and 10 lateral bars of L100x100x10 profile; 62 diagonal bars made of profile L60x60x6, and on the lateral faces there are rectangular pipes 80x80x6, made of the S355J2 steel" [6], [8].

Setting the Work Model using FEA Facilities

From the static point of view, the mast is a spatial structure made of many beams rigidly fixed at their nodes and statically undetermined [1], [2], [3], [4], [5], [7], [8]. For such a complex structure, the best method to determine the displacements and the deformed shapes is the "method of displacements" [9], which is the Finite Elements Method's basis. In this work, the authors used the ANSYS 10.0 software in order to achieve the dynamic analysis and each beam was considered a finite element. Two types of elements were used, i.e.: BEAM189 for bars (according to [11], „BEAM189 is an element suitable for analyzing slender to moderately stubby/thick beam structures, based on Timoshenko beam theory. Shear deformation effects are included. It has six or seven degrees of freedom at each node and includes stress stiffness terms. The provided stress stiffness terms enable the elements to analyze flexural, lateral, and torsional stability problems") and LINK10 for anchors (according to [11], "LINK10 is a 3-D spar element having the unique feature of a bilinear stiffness matrix resulting in a uniaxial tension-only (or compression-only) element. With the tension-only option, the stiffness is removed if the element goes into compression. It is useful for static guy-wire applications where the entire guy wire is modeled with one element").

This mast is a prototype and its important particularity is the fact that its structure is composed in a great majority of bars of L-profile, the axes of which do not intersect in nodes. The lack of intersection of these axes is given, on the one hand, by technological consideration of achieving welds and on the other hand by the necessity of extracting the upper section through the lower one at the time of telescoping operation.

With the aim of realizing an appropriate model for the proposed dynamic analysis, the mass of each beam was automatically determined and at nodes were concentrated all half values of each mass of beams that intersect them.

The work models for the sections of this prototype are shown in Figures 3, 4, 5 and in Figure 6 is presented the crown-block's model, considered to be important in the dynamic analysis, due to its heavy components' masses.

After assembling the three sections, resulted after meshing a calculation model including, from geometrical point of view, 212 points and 346 lines. As a consequence of this modeling, the mast is a structure with many degrees of freedom (over 600), taking into account that each node has three translations (along OX, OY and OZ axes).

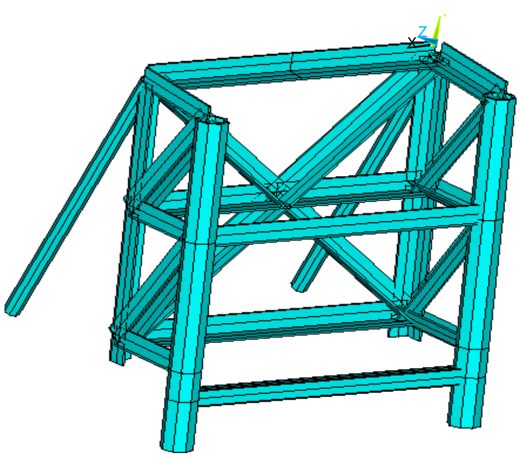

Fig. 3. Fixed section model

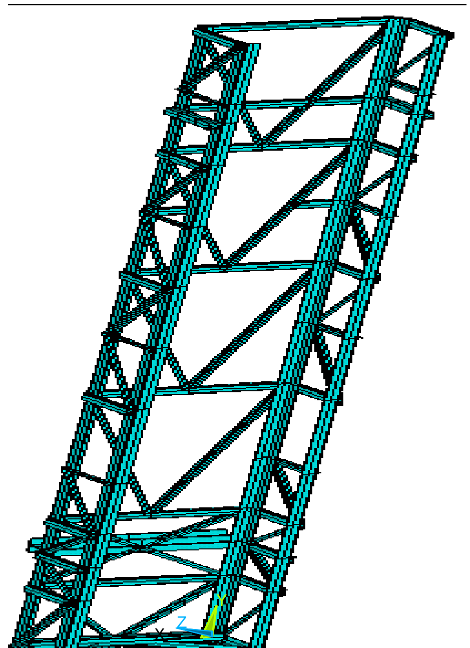

Fig. 4. Lower section model

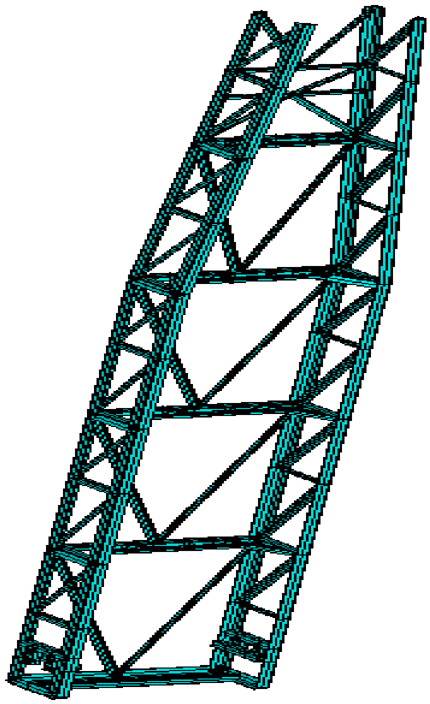

Fig. 5. Upper section model

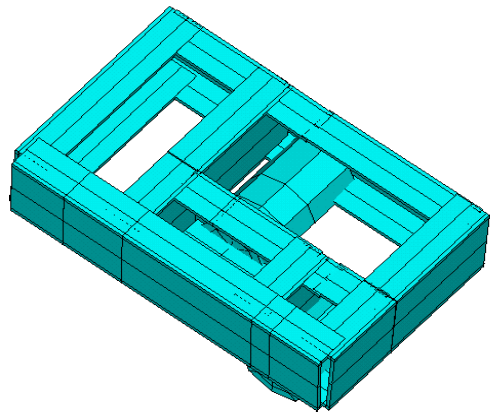

Fig. 6. Crown-block's model

Obtaining the Natural Frequencies and the Mode Shapes

It must be specified that this prototype of mast was subjected to a static analysis in two cases of loading ([6], [8] and [10]): in the case of the overload test, as an exceptional loading, and in the case of wind action with a velocity of 70 km/h, as a temporary action. Both static analyses showed an unsatisfactory behaviour of the mast, due to its initial design of a zone of the upper section, with beams of L60x60x6 profile [13], in the crossing zone from prism shape to truncated pyramid shape (as it can be seen in figure 5). So, after the redesign of this zone by replacing the indicated beams with other ones, with angle profile L100x100x10 [13], the level of stresses decreased under the allowable value.

In the following will be presented the results obtained in the case of free dynamic vibration for both cases- before and after redesign, with the necessary observations and conclusions. All these dynamic parameters (natural frequencies/angular frequencies, mode shapes) must be known, because during well operations there are many situations when dynamic loadings/perturbation factors are present and influence directly the mast's behaviour: a sudden pulling out of the drill string caused by downhole equipment jamming, gusty wind, wind action in the case of drill pipes stacking on a single side of the mast etc.

For a better understanding the form of mode shapes, firstly in Figures 7 and 8 there is shown the unloaded model shape of the mast in two planes. Then, in Figures 9…13, the mode shapes corresponding to the first five natural frequencies before redesigning are presented.

In Table 1, the first ten natural frequencies, with corresponding angular frequencies and periods are presented as results of dynamic analysis using FEM.

Analysing the first five natural frequencies and their mode shapes, it can be observed that:

- the first three natural frequencies have values quite far apart;

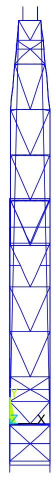

Fig. 7. XOY-plane view

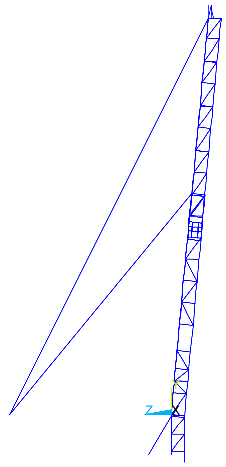

Fig. 8. YOZ-plane view

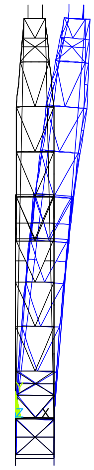

Fig. 9. Mode shape 1

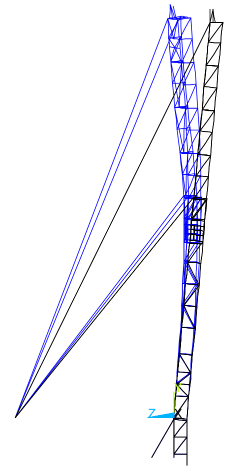

Fig. 10. Mode shape 2

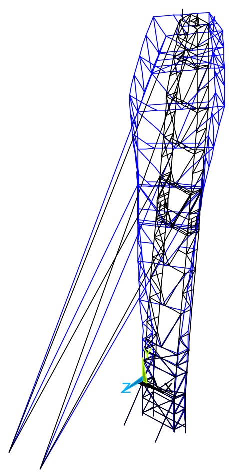

Fig. 11. Mode shape 3

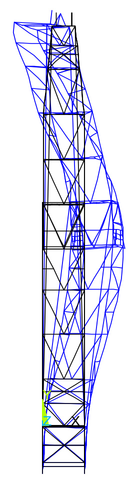

Fig. 12. Mode shape 4

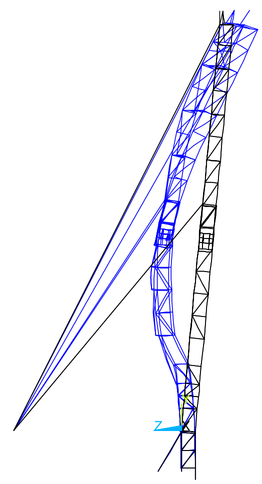

Fig. 13. Mode shape 5

Table 1. Dynamic parameters before redesigning

Mode shape no.	Natural frequency f [Hz]	Angular frequency, p [rad/s]	Period T [s]
1	2.7112	17.035	0.369
2	5.0036	31.438	0.199
3	7.3409	46.124	0.136
4	8.9468	56.214	0.112
5	9.5348	59.909	0.105
6	14.605	91.766	0.068
7	17.660	110.96	0.057
8	20.459	128.55	0.049
9	21.904	137.62	0.045
10	26.052	163.69	0.038

- between the natural frequencies no. 3 and 4 and also between no. 4 and 5, the difference is under 40%, which means that a perturbation factor having the frequency in that interval of values can influence an entering in the situation of the resonance phenomenon, because such a value is corresponding to a difference smaller than 20% of each of these natural frequencies;
- for p_1= 17.035 rad/s, the mode shape corresponds to an oscillation in XOY-plane;
- for p_2= 31.438 rad/s, the mode shape corresponds to an oscillation in YOZ-plane;
- for p_3= 46.124 rad/s, the mode shape corresponds to a general torsional oscillation;
- for p_4= 56.214 rad/s, the mode shape is an oscillation in XOY-plane, but with two sinusoids;
- for p_5= 59.909 rad/s, the mode shape is an oscillation in YOZ-plane, but with several inflexions.

Table 2. Dynamic parameters after redesigning

Mode shape no.	Natural frequency f [Hz]	Angular frequency p [rad/s]	Period T [s]
1	2.7063	17.004	0.370
2	4.9987	31.408	0.200
3	7.3168	45.973	0.137
4	8.9495	56.231	0.112
5	9.5336	59.901	0.105
6	14.599	91.728	0.068
7	17.657	110.942	0.057
8	20.437	128.409	0.049
9	21.89	137.539	0.046
10	26.038	163.601	0.038

After the redesign of the beams of the crossing zone from prism shape to truncated pyramid shape situated at the upper section (L60x60x6 replaced by L100x100x10), the obtained dynamic parameters are presented in Table 2. The mode shapes resemble with the ones previously presented. The constructive modification did not influence in a significant manner the dynamic parameters of the mast in case of free vibrations, but it should be noted that it is very important and necessary for the general resistance of the mast in the case of exceptional or temporary actions [10].

Conclusions

1. The mast is a multi-degree of freedom structure and, from the static point of view, it is a multiple statically indeterminate structure.

2. In order to determine its natural frequencies and, respectively, its angular frequencies, periods and mode shapes, the computer program ANSYS 10.0 was used. There were presented the first ten values for each dynamic parameter and there were showed the first five mode shapes in two cases: before and after redesigning a critical zone (for the static behaviour) situated in the crossing area from prism shape to truncated pyramid shape. The redesign of the indicated zone for the static situation did not influence in a significant manner the dynamic parameters values.

3. The obtained values of natural frequencies showed that the first three are quite far apart and between the natural frequencies no. 3 and 4 and also between no. 4 and 5, the difference is under 40%, which means that a forcing factor having the frequency in that interval of values can influence an entering in the situation of the resonance phenomenon, because such a value is corresponding to a difference smaller than 20% of each of these natural frequencies.

4. A forcing factor like gusty wind can influence a vibration as it follows: transversal (on mast) wind action can lead to a vibration as mode shape no. 2 is shown and longitudinal wind action to a vibration as mode shape no. 1 is presented.

5. A sudden pulling out of the drill string caused by downhole equipment jamming can be a factor that can lead to a mast vibration like mode shape no. 2.

6. In the case of drill pipes stacking on a single side of the mast, combined with wind actions, a vibration like mode shape no. 3 can occur (torsional vibration) if the wind direction is perpendicular on the diagonal of the mast's cross-section, but also vibrations like mode shapes no. 1 or 2 can appear, if the wind direction is transversal or longitudinal to the mast.

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Studiul comportării unui mast transportabil de 500 kN sarcină maximă la cârlig în timpul vibraţiilor libere

Rezumat

Forajul unei sonde, urmat sau chiar întrerupt uneori de lucrări de intervenţie sau reparaţie, este una dintre cele mai costisitoare şi periculoase activităţ ce se desfăşoară în câmpurile petroliere. Cedarea uneia dintre componentele unei instalaţii, în particular a mastului său, poate conduce către costuri foarte mari, nedorite. Problema vibraţiei masturilor este o preocupare a practicienilor forajişti şi, de asemenea, a proiectanţilor de utilaj petrolier. Este evident că, pentru o anumită construcţie a mastului, este necesar a i se cunoaşte dinainte valorile frecvenţelor proprii, pentru ca acestea să poată fi evitate pe timpul funcţionării instalaţiei. În această lucrare este analizat comportamentul dinamic al unui mast transportabil de 500 kN sarcină maximă la cârlig în cazul vibraţiilor libere. Mastul este alcătuit din trei tronsoane: unul fix, unul inferior şi unul superior, toate compunând o structură spaţială complexă, static nedeterminată. În ansamblul său, mastul este alcătuit din bare drepte cu diferite secţiuni transversale, fiind legat la şasiul autocamionului prin intermediul a patru ancore de rezistenţă: două fixate de zona coroanei geamblacului şi două de zona superioară a tronsonului inferior. Autorii au utilizat analiza cu elemente finite cu scopul de a determina primele zece frecvenţe proprii şi corespunzătoarele forme proprii de oscilaţie pentru primele cinci. Sunt indicaţi factorii care pot produce vibraţii forţate în timpul funcţionării instalaţiei şi este evidenţiat pericolul apariţiei fenomenului de rezonanţă cauzat de aceştia.