The Determination of Ultimate Releasable Hook Load in Casing Running Through an Air-filled Wellbore

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Abstract. The pipe is frequently stuck in casing running through the wellbore drilled by air hammer, and releasing part of suspending weight is commonly practiced to solve this problem, which would engender the strong axial vibration of casing string and make the operation in high risk when wellbore is filled with air or gas. In this paper, the propagation mode of the stress wave has been distinguished based on explicit dynamic finite analysis, where various length of string and released load have been considered. The influence of damping to the fluctuation characteristics of hook load has been discussed, and Rayleigh damping has been applied. With the investigation of the stress wave characteristics in the vibration of casing string, a new method to determine the ultimate releasable hook load in casing running through an air-filled wellbore has been proposed. The results have been validated in an oilfield of western China. The methodology and approach presented in this paper can be used to guide operation in casing running practices by engineers.

Introduction

Compared with the mud drilling, air drilling technology has many advantages, e.g. increase the penetration rate, reduce the lost circulation, decrease the damage to formation and extend the bit life[1-3]. Nevertheless, replace the drilling fluid from air to mud before casing running may induce complex situations, such as lost circulation, borehole wall sloughing, etc., which will result in non-productive rig time and added cost[4-7]. Hence, running casing directly in air-filled wellbore is increasingly used.

It should be noted that the wellbore drilled by air hammer is not smooth in conglomerate, shown as in Fig.1[8]. The bulge is easily formed in the wellbore and the stuck of casing string occurs frequently in casing running. Part of string suspending weight is commonly released to generate a corresponding force at the bottom end of casing string (named resistance load) to break the bulge. However, axial vibration of casing string would engender when the bulge is broken, which produce additional dynamic load on the hook. As a result, the hook load may exceed the ultimate load of rig, especially in air condition due to small buoyancy and low dumping force.
Much researches have been carried out about the mechanics characteristic of casing string. Mason et al.[9, 10] presented a number of papers devoted to various issues related to operational difficulties and predictions of casing running loads. Maidla and Wojtanowicz [11] used the soft string model to predict casing running performances of four directional wells with the well path restricted to the vertical plane. The calculated hook loads were consistent with actually measured results. Stefan Miska et al.[12] take the effect of wellbore torsion into consideration, and developed a three-dimensional model to calculate the axial force and the contact force along the casing. McSpadden et al.[13] discussed the axial force, shear moment and stress along the length of the casing string with stiff string model, and demonstrated that optimized casing-design efficiency may be achieved by avoiding overly conservative and costly design for HP/HT and extreme-temperature wells.

However, the additional dynamic load induced by the vibration of casing string has not been explored currently. In this paper, the propagation behaviors of stress wave in casing string are investigated, and a new method is developed to determine the ultimate releasable hook load in casing running. The results would be helpful to decrease the operational risks of casing running.

**Establish of the Model**

In this paper, two finite element models of the casing string have been established (the length of casing string is 1500m in model 1 and 3400m in model 2), where the casing is approximated by general beam elements with six degrees of freedom at each node to account for all possible physical displacements. The propagation behaviors of stress wave in casing string have been investigated with ABAQUS code. It should be noted that the contact has not been considered in the determination of ultimate releasable hook load in this paper, cause the contact between casing string and wellbore would weaken the vibration.

The top end of the casing string is constrained, as shown in Fig.2, then the fluctuation of the hook load would be obtained by extracting the reaction force on the constrained point. Three analysis steps have been applied to investigate the propagation behaviors of stress wave in casing string. In the first step, the gravity acceleration (9.8m/s²) was applied to the whole model smoothly. In the second step, a resistance load was applied at the bottom end of casing string, as shown in Fig.2. In the third step, the resistance load was released suddenly, which represents that the bulge was broken instantaneously.
The Stress Characteristics of Casing String in Vibration

Undamped System

Based on the explicit dynamic finite element analysis, the fluctuation characteristics of the hook load for an undamped system can be obtained, as shown in Fig.3.

In the third step, it can be found that the fluctuations range of the hook load, including the static loads generated by suspending weight of casing string and the additional dynamic load produced by the vibration of casing string, keeps constant due to the conservation of energy.

The range of fluctuation is two times of the resistance load both in model 1 and model 2, which means that the additional dynamic load is equal to the resistance load in an undamped system (see Table 1). The results show that the additional dynamic load is independent with the length of casing string.

As an quintessential example, the maximum hook load of rig ZJ90/6750 is 6750kN[14]. Considering the complex down hole force conditions, a safety factor of 1.2 is used to provide some safety margin, then the max allowable hook load should be 5625kN. However, the fluctuation characteristics of hook load in model 2 shows that the maximum hook load is 5714.7kN due to the sudden release of resistance load, which greatly increases the operation risk of casing running.
Table 1. - The Fluctuation of the Hook Load in an Undamped System.

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<tbody>
<tr>
<td>Model 1</td>
<td>2410.9</td>
<td>300</td>
<td>2711.1</td>
<td>2110.4</td>
<td>600.7</td>
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<tr>
<td>Model 2</td>
<td>5464.8</td>
<td>250</td>
<td>5714.7</td>
<td>5214.8</td>
<td>499.9</td>
<td>2.00</td>
<td>249.9</td>
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The propagation velocity of stress wave in casing string could be calculated with Eq.(1)[15-16]

\[ c = \sqrt{\frac{E}{\rho}} = 5167.9 \text{ m/s} \]  

According to the Eq. (1), a time of approximate 0.29s is needed for the stress wave propagate from bottom end to top end of a casing string with 1500m length. Fig.4 shows the axial stress distribution along the casing string with red line, while the blue dashed line means axial stress in casing string before the sudden release of the resistance load, where the negative axial stress means the compression. When resistance load suddenly released, the axial stress at the bottom end of casing string would instantly reach to zero. At the same time, a tension stress wave engendered and transmitted towards the top end of casing string, shown as in Fig.4a and Fig.4b. After the stress wave arrived to the top end (fixed end), the wave would be reflected. The wave maintains as a tension wave[17], and keeps on propagation to the bottom end, as shown in Fig.4c, Fig.4d, Fig.4e. Once the stress wave arrived to the bottom end again, the tension wave would reflected into the compressive wave[17], and then transmit towards the top end in the same velocity, as shown in Fig.4g, Fig.4f, Fig.4h.

The fluctuations of strain energy in casing string were shown in Fig.5. It can be found the strain energy increased under the action of tension wave (0s ~ 0.58s), while decreased under the action of compressive wave (0.58s ~ 1.16s). In an undamped system, this cyclical fluctuation always exists in the casing string.

Figure 4. Axial Stress Distribution in Casing String Over Time.
Damped System

As damping always exists in actual mechanical systems, the energy would be gradually dissipated in a damped system, and the range of fluctuation would be gradually decreased to zero. However, it is difficult to identify the constitute of a system's damping due to its complex mechanism.

In this paper, the Rayleigh damping model is assumed, which provides a convenient abstraction to damp lower (mass-dependent) and higher (stiffness-dependent) frequency range behavior[18]. In Rayleigh damping model, the matrix of damping $[\mathbf{C}]$ is assumed as the linear combination of mass matrix $[\mathbf{M}]$ and stiffness matrix $[\mathbf{K}]$ as follows:

$$[\mathbf{C}] = \alpha [\mathbf{M}] + \beta [\mathbf{K}]$$  \hspace{1cm} (2)

where $\alpha$ and $\beta$ are the damping factors. Based on Eq.(2), damping ratio $\xi_i$ can be expressed as[19-21]

$$\xi_i = \frac{\alpha}{2\omega_i} + \frac{1}{2} \beta \omega_i$$  \hspace{1cm} (3)

where $\omega_i$ is the $i$th order natural frequency of the string. Hence, the damping coefficient $\alpha$ and $\beta$ can be determined with the natural frequency and damping ratio.

According to the vibration theory of a straight bar, the natural frequency of the longitudinal vibration can be calculated with Eq.(4)[22]

$$f_i = \frac{2i-1}{4L} \sqrt{\frac{E}{\rho}} \quad (i=1,2,...)$$  \hspace{1cm} (4)

Take the model 1 as an example, it can be obtained $f_1 = 0.86$ Hz, $f_2 = 2.58$ Hz, $f_3 = 4.30$ Hz ...

The response near the top end of casing string in model 1 can be obtained by frequency response analysis, as shown in Fig. 6, where the top end of casing string is constrained and an axial excitation $f(\Omega) = A * B(\Omega) e^{\theta(\Omega) + \theta_0 + \zeta} \Omega$ is applied at the bottom of the string. It can be found that the response of casing string is large when the excitation frequency close to the first few natural frequencies.
Assume that the damping ratios of the first two order natural frequency equal to 0.01, the damping coefficient $\alpha=0.0129$, $\beta=0.0058$ can be obtained according to Eq. (3). Applied this Rayleigh damping to the model 1, the fluctuation characteristics of hook load can be obtained in Fig.7a. The results shows that the fluctuation range is 1.831 times of the resistance load, and the additional dynamic load is 0.831 times of the resistance load.

Assume that the damping ratios of the first two order natural frequency equal to 0.02, the damping coefficient $\alpha=0.0258$, $\beta=0.0116$ can be obtained according to Eq. (3). In this case, the fluctuation range of hook load is much small and decayed rapidly, as shown in Fig.7b. It can be found that the fluctuation range is 1.629 times of the resistance load, and the additional dynamic load is 0.629 times of the resistance load.

The results show that the fluctuation range of the hook load decreases with the increasing of the damping, and the hook load reaches stable quickly with large damping. Hence, the additional dynamic load in damped system is smaller than undamped system.

Table 2. The Influence of Damping on the Additional Dynamic Load.

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<td>488.8</td>
<td>1.629</td>
<td>188.8</td>
<td>0.629</td>
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(a) damping ratio=0.01  
(b) damping ratio=0.02

Figure 6. The Response of the Wellhead Under Different Excitation Frequency.

Figure 7. The Influence of Damping on the Additional Dynamic Load.
The Determination of Ultimate Releasable Hook Load in Casing Running

Although damping always exists in actual mechanical system, it can be found that the additional dynamic load of the hook load is much larger in an undamped system from the above discussion. Hence, the ultimate releasable hook load should be determined according to fluctuation characteristics in an undamped system for safety consideration.

The ultimate hook load of the drill rig is denoted as $F_{max}$, the suspending weight of the casing string is denoted as $W$. If the stuck happened in casing running, and the released hook load is denoted as $f$, then the hook load becomes into $W-f$. With the suddenly release of the resistance load, the additional dynamic load in an undamped system is $f$, which means the hook load fluctuates from $W-f$ to $W+f$.

In order to ensure the safety of the casing running operation, a safety factor $k$ is assumed and the released hook load $f$ should be

$$f \leq \frac{F_{max}}{k} - W$$

Eq.(5) can be applied as a guide in casing running operation. Once the stuck of casing string occurs, operators should determine the ultimate releasable hook load according to the Eq. (5).

As an example, the maximum hook load of rig ZJ90/6750 is 6750kN, the maximum static suspending weight of the casing string with 3400m length is 5464.8kN in air-filled wellbore. If a safety factor of 1.2 is assumed, the ultimate releasable hook load can be determined as follows:

$$f \leq \frac{F_{max}}{k} - W = 6750/1.2 - 5464.8 = 160.2kN$$

While in mud filled wellbore, assumed the density of mud is 1.35g/cm$^3$, then the corresponding buoyancy factor is 0.828, and the ultimate releasable hook load can be determined as follows:

$$f \leq \frac{F_{max}}{k} - W = 6750/1.2 - 5464.8\times0.828 = 1100.1kN$$

It can be found that the ultimate releasable hook load in air-filled wellbore is much smaller than in mud-filled wellbore.

Summary

The safety margin of rig load is not large in air-filled wellbore, special attention should be paid to the additional dynamic load caused by sudden release of the resistance load. The additional dynamic load is equal to the resistance load in an undamped system, which is independent with the length of casing string.

The additional dynamic load decrease with the increasing of damping, and the fluctuation of hook load decay rapidly when a large damping is taken into account. Hence, increasing the damping of the system can benefit to the safety of casing running operation.

For safety considerations, the proposed calculation formula is suggested to determine the ultimate releasable hook load in casing running through an air-filled wellbore.

Acknowledgments

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