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Multi-axial fatigue life prediction of drill collar thread in gas drilling

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ABSTRACT

With its advantages of lost circulation prevention, drilling speed improvement and reservoir protection, gas drilling technology has been widely applied in Sichuan and Xinjiang oilfields in China. However, drill collar failures have often occurred under high weight on bit (WOB) during gas drilling. These incidents have not only caused serious economic loss but hampered the development and application of gas drilling. Finite element analysis is used to determine the drill collar thread stress distribution and, using simulation of drill string dynamics, multi-axial fatigue life theory is used to calculate the life of a standard API drill collar connection. The computed results reveal the early drill collar fatigue failures in gas drilling. Then, the multi-axial fatigue life of drill collar with double shoulder thread is analyzed under the same loads. Analysis shows that the fatigue life of a double shoulder thread is some thirty times that of the API thread. So drill collar with double shoulder thread could be an efficient way to solve the fatigue failure problems of drill collar in gas drilling. The work presented in this paper can provide theoretical foundations for safe and efficient drilling with gas.

1. Introduction

Gas drilling is an underbalanced drilling technology using air, nitrogen or natural gas as circulating medium. Originating from the U.S. in the 1950s, gas drilling technology has been widely applied around the world owing to its outstanding advantages in drilling speed improvement, formation protection and reservoir discovery. With the gradually improved theoretical research and field application, gas drilling has flourished in many oil and gas fields of China. Gas drilling is mainly used for lost circulation prevention in leakage formations, drilling speed improvement in high abrasiveness formations, and reservoir protection in low-permeability and tight gas reservoirs. However, a large number of incidents of drilling tool failure have been reported during the application of gas drilling. Statistics show that drill collar failure and cross-over sub failure account for approximately 54% of drilling tool failures. Among the drill collar thread fracture incidents, 70% of them occurred at box thread and 30% occurred at pin thread. These drilling tools failure problems, if not solved properly, will not only hamper the possibility of drilling into deep formation and complex strata with gas but influence the improvement of gas drilling speed.

Previous research has indicated that fatigue failure is the most frequent drill string damage [1] under high WOB and that the drill collar thread is subjected to serious fatigue failure in gas drilling [2–5]. Former researchers generally adopt the uniaxial fatigue theory to study fatigue life of drill collar. In gas drilling, however, drill collars are subjected to a series of complex dynamic and static loads such as axial force, bending moment and make-up torque. Uniaxial fatigue theory is inadequate to deal with these complex forces arising from drill string motion characteristics and the combined effects of complex external loads. In order to improve this situation,

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multi-axial fatigue theory is used to study the fatigue life of drill collars under various external loads on the basis of drill string dynamics and FEA (finite element analysis). The multi-axial fatigue lives of an API collar and a double shoulder collar are predicted and compared to reveal the mechanism of early failure. The methods and achievements of this research can provide a theoretical basis for further developing drill collar design and drilling into deeper formation with gas.

2. Multi-axial fatigue life theory

Fatigue damage under multi-axial cyclic loading conditions can occur where two or three stress (or strain) components change periodically and independently over time [6]. The importance of multi-axial fatigue was realized in the late 1970s; and since the late 1980s, abundant research has been carried out related to strain-based multi-axial fatigue criteria and local stress–strain analysis of notch roots under proportional and non-proportional loading [7–9]. Although the theory of multi-axial fatigue has been widely applied in aerospace, nuclear power and transportation industries in recent years [10–12], its application in drill string fatigue life prediction of gas drilling is rarely reported.

2.1. Multi-axial cyclic stress–strain relations

The external loads acting on drill collars are very complex in the gas drilling process. According to the results of field tests and laboratory simulation, the amplitude and vibration periods of cyclic loads caused by axial, lateral and torsional vibration can be regarded as approximately constant when drilling in the same stable strata. Therefore, under these conditions, it can be assumed that the cyclic loads on the drill string are proportional loading. It is also assumed that each component of the stress tensor of increases proportionally, with fixed direction of principal stress axes. Shang D.G. et al. [6] found that the equivalent cyclic stress–strain relations under multi-axial proportional loading conditions were consistent with that under uniaxial loading conditions. According to the Osgood–Ramberg uniaxial tensile-compressive cyclic stress–strain relations, Eq. (1) [6,16–17] can account for the cyclic stress–strain relations of the drill collar material-42CrMo steel [13–15] under multi-axial proportional loading:

$$\frac{\Delta\varepsilon_{eq}}{2} = \frac{\Delta\sigma_{eq}}{2E} + \left(\frac{\Delta\sigma_{eq}}{2K'}\right)^{\frac{1}{n'}} \quad (1)$$

where E is the elasticity modulus (MPa); $\Delta\sigma_{eq}$ is the Von-Mises equivalent stress amplitude (MPa); $\Delta\varepsilon_{eq}$ is the Von-Mises equivalent strain amplitude; n' is the cyclic strain hardening exponent of drill collar material; K' is cyclic strength coefficient of drill collar material. They can be obtained by the following equations:

$$\Delta\varepsilon_{eq} = \left(\frac{2}{3}\Delta\varepsilon_{ij}\Delta\varepsilon_{ij}\right)^{\frac{1}{2}} \quad (2)$$

$$\Delta\sigma_{eq} = \left(\frac{3}{2}\Delta S_{ij}\Delta S_{ij}\right)^{\frac{1}{2}} \quad (3)$$

$$\Delta S_{ij} = \Delta\sigma_{ij} - \Delta\sigma_{kk}\delta_{ij}/3 \quad (4)$$

$$n' = b/c \quad (5)$$

$$K' = \sigma'_f/\left(\varepsilon'_f\right)^{n'} \quad (6)$$

where ΔS_{ij} is the differential stress range (MPa); b is the fatigue strength index of drill collar thread material; c is the fatigue ductility index; σ'_f is the fatigue strength coefficient of drill collar thread material; ε'_f is the fatigue ductility coefficient [12]. These parameters can be obtained from following equations:

$$b = -\frac{1}{6}\lg\left(\frac{2\sigma'_f}{\sigma_b}\right) \quad (7)$$

$$\sigma'_f = 1.19\sigma_b\left(\sigma_f/\sigma_b\right)^{0.893} \quad (8)$$

$$\varepsilon'_f = 0.630 \times \varepsilon_f \times \left[1 - 81.8(\sigma_b/E)\left(\sigma_f/\sigma_b\right)^{0.179}\right]^{-1/3} \quad (9)$$