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Critical helical buckling load assessment of coiled tubing under axial force by use of the explicit finite-element method

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ABSTRACT

Previous theoretical formulations for helical buckling of drill strings vary significantly and are mostly proposed for the linear questions. But there are a little no-linear questions in the mechanical behaviour of tubulars. Explicit finite element analysis (FEA)method has the ability to consider geometric details and nonlinearities. This paper builds an explicit FEA model to describe the behaviors of comprehensive buckling and transmission of axial force for coiled tubing (CT) with residual bending in a horizontal well. The calculational results show that the CT with residual bending is easier to buckle than a straight CT. For the CT with an initial sinusoidal shape, the parameters of initial amplitude and initial pitch are inversely proportional to the helical buckling force, and the outer diameter (*OD*) is proportional to the helical buckling force. In the process of axial force transmission, the parameters of initial amplitude and frictional coefficient are inversely proportional to the axial force, the *OD* and initial pitch are proportional to axial force. Residual curvature in coiled tubing appears to have only a small effect on its downhole performance, based on FEA modeling of CT with sinusoidal curvature.

1. Introduction

The applications of coiled tubing (CT) operating system used in drilling operations has achieved considerable economical benefits (Krueger et al., 2013; Krueger and Pridat, 2016) Increasing weight on bit (WOB) is an affective measure to improve drilling efficiency. But WOB is limited by the buckling load of CT. Buckling can intensify the bending stress and lead to fatigue failure over time. When a CT is starting to buckle, it is generally believed that it will first change into a sinusoidal-buckling shape and then to helical buckling (Lubinski, 1950; Lubinski and Woods, 1953). first time studied the sinusoidal and helical buckling of straight tubulars in incline wells using the method of energy (Paslay and Bogy, 1964) (Dawson and Paslay, 1984). derived the well-known critical sinusoidal (Eq. (1)) and helical (Eq. (2)) buckling load expression in an inclined wellbore.

$$F_{cr} = 2\sqrt{\frac{EIq\sin\alpha}{r_c}} \tag{1}$$

$$F_{Cr}^{*} = \gamma_1\sqrt{\frac{EIq\sin\alpha}{r_c}}\cdot\gamma_1 = 2\sqrt{2} \tag{2}$$

From then on, many researchers (Chen et al., 1990; Deli et al., 1998; Miska et al., 1996; Wu and Juvkam-Wold, 1993) worked on the prediction of buckling and post-buckling behaviors of drilling strings in wells, and found the same formulas with that derived by (Paslay and Bogy, 1964) (Dawson and Paslay, 1984). The critical sinusoidal buckling loads proposed by the above researchers are the same. But the critical helical buckling loads are different, and the values of critical helical buckling loads proposed by the above researchers are given in Table 1.

However, these models typically assumed that the tubing was initially straight in wellbore. This assumption is suitable for tubing like drill pipe, casing. But the initial shape of CT is bent when it is entered a wellbore. The initial shape of a CT is usually assumed to sinusoidal or helical bending (Qiu, 1997). studied the critical buckling load of a CT with initial sinusoidal bending in incline and horizontal wells, and derived the helical (Eq. (4)) buckling load expressions.

$$F_{Cr}^{*} = 4\sqrt{\frac{f_2 f_3}{f_1^2}}\sqrt{\frac{2EIq\sin\alpha}{r_c}} \tag{3}$$

$$f_1 = 1 - \frac{1}{2}A_i^2 \tag{4}$$

$$f_2 = 1 - A_i + \frac{1}{2}A_i^2 + \frac{3}{8}A_i^3 + \frac{3}{8}A_i^4 \tag{5}$$

$$f_3 = 1 - \frac{1}{2}A_i^2 + \frac{3}{8}A_i^4 \tag{6}$$

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Table 1
The values of parameter γ_1 provided by different researchers.

Researchers	γ_1
Lubinski (1950)	2.4
Chen et al. (1990)	2.83
Wu and Juvkam-Wold (1993)	3.66
Miska (1995)	5.56
Mitchell (1997)	5.5
Deli et al. (1998)	2.8

(Zheng and Adnan, 2005) assumed that the initial shape of a CT is helical bending, and studied the maximum penetrating depth of a CT in a horizontal well (Qin and Gao, 2016). considered the initial form of CT is sine and cosine bending respectively, and derived the critical helical (Eq. (7)) buckling load expressions,

$$F_{cr}^{*} = \frac{2}{\sqrt{(0.678A_i^2 + 0.25A_i + 0.5)}}\sqrt{\frac{EIq\sin\alpha}{r_c}} \tag{7}$$

Previous studies about the buckling behaviour of a CT were mainly carried out by analytical and experimental methods, and the two methods have their own advantages and disadvantages respectively. In analytic methods, boundary conditions of a mechanical model are usually simplified to linear. In fact, bound conditions、load-displacement curves for a buckling problem are nonlinear, and the current wellbore makes it more nonlinear (Akgun et al., 1996). In experimental methods, experimental results are usually affected by the accuracy of equipment and the size of the specimen. Explicit nolinear finite element anlysis (FEA) model is a good candidate for solving these non-linear problems (Hajianmaleki and Daily, 2014). Simultaneously, it can more intuitively show the mechanical behaviour of a CT. For these reasons, an explicit finite element method is used to study the mechanical behaviour of a CT in horizontal wells. The studies of this paper allow for accurate job design to operate CT in the wellbore.

2. Mechanical model

2.1. Initial configuration of a CT in wells

Fig. 1 illustrates the schematic of a CT operating system, a CT is pulled out from the roller, enters the injector through the gooseneck, and is finally removed out from the injector. . When a CT is spiral twined on the roller, an additional torques are made on the cross sections of the CT. The configuration of a CT is changing four times from the roller to the injector. When the tube passes through the injector, it straightens and stretches the CT and recuces the CT's spiral effects. Finally, the level of bending is reduced as it is lowered into the well. Thus, this study agrees with the assumptions of (Stefan Miska, Weiyong Qin and Gao, 2016), the configuration of coiled tubing in wells is belong to spatial buckling rather than plane buckling. As shown in Fig. 2,

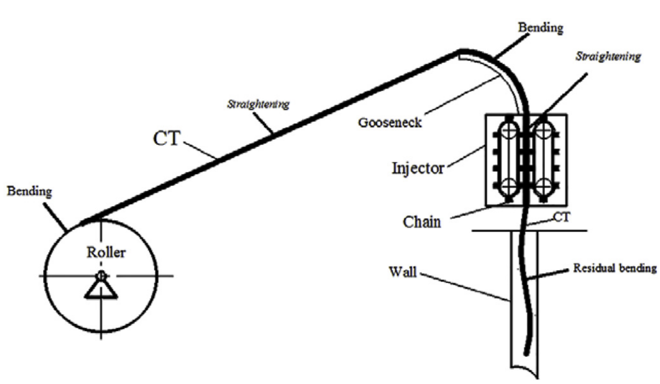

Fig. 1. Schematic of a CT operating system.

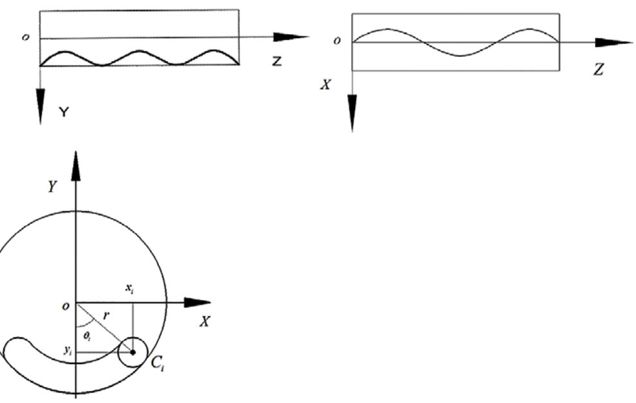

Fig. 2. Mechanical model.

the initial form of CT is sinusoidal buckling, and it lies on the bottom of a well and continuously contacts with borewall under the action of gravity. The initial position of a point on the axis of the CT is denoted by $C_i(x_i, y_i, z_i)$,where

$$\begin{cases} x_i = r_c \sin\theta_i \\ y_i = -r_c \cos\theta_i \\ \theta_i = A_i \sin\frac{2\pi z}{P_i} \end{cases} \tag{8}$$

2.2. Explicit finite-element modelling

Under an axial load, the bent microelement of CT is bearing a large axial stress and a less shearing stress. Beam element B31-3D of ABAQUS soft is built as the theory of Timoshenko, the axial stress and shearing stress on the cross section of B31-3D are considered at the same times. Meanwhile, B31-3D elements can transmit in three dimensions according for helical shapes and 3D motions of a CT. Thus, The CT is mashed using the element of B31-3D. The wellbore is modeled as a rigid body with the rigid element R3D4.

As shown in Fig. 3, a CT is lying on the bottom of bore hole, and contacting with the borewall continuously. Constraint 1 is loaded on the bottom of CT and it fixed the CT to move and rotate around any axis. Constraint 2 is loaded on the top of CT and it enables a CT to move and rotate around the z-axis only. Fig. 4 shows the loading curves. At the first time step of the explicit FEA model, the gravity is starting to be loaded and reaches its value in a smooth fashion. In the second time step, the gravity is keeping is value, meanwhile, the axial load is starting to apply and reaches its value in a smooth fashion too.

3. Helical bucling analyses

In the FEA model of helical buckling analyses, the length of CT is defined as one initial pitch. and the element size of the CT is in the length of 50 mm. Normal steel material properties for modulus of elasticity (206 GPa) and Poisson's ratio (0.3) were used. To characterize the machanical behaviour of CT under an axial force, axial force vs. axial displacement in a horizontal wellobre is analyzed and the result is presented in Fig. 5.

Point "A" in Fig. 5 shows the onset of sinusoidal buckling, point "B" is the starting point of helical buckling. Before the point "A", the CT form is not changed under the axial force. In the range of point "A" and "B", the CT is deformed to sinusoidal buckling, and the relationship between compressive load and deformation is expressed as linear. After the point "B", the CT is deformed from sinusoidal buckling to helical buckling. The helical buckling CT makes more contact force and frictional drags with the borewall. Thus, in this state, the compressive load is increasing enormous with a little deformation.

When solving a CT's buckling load using theoretical method, the CT