Journal of Natural Gas Science and Engineering 30 (2016) 182–194

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

The effect of residual bending on coiled tubing buckling behavior in a horizontal well

Xing Qin*, Deli Gao

MOE Key Lab of Petroleum Engineering, China University of Petroleum, Beijing, 102249, China

ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form
29 January 2016
Accepted 13 February 2016
Available online 16 February 2016

Keywords:
Coiled tubing
Residual bending
Buckling
Horizontal well

ABSTRACT

This paper builds an analytical model to describe the comprehensive buckling behavior of CT (coiled tubing) with residual bending in a horizontal well. The new model is built on the basis of beam-column theory and solved by the Galerkin method of weighted residuals. The initial configuration of CT with residual bending are assumed to be in two typical trigonometric shapes, sine mode or cosine mode. By using the new buckling equations, critical buckling force and radial contact force are calculated accounting for the residual bending. Axial compressive displacement and maximum bending moment are also calculated. The calculation results show that a CT with residual bending behaves more easily to buckle than a straight CT, and the maximum contact force of CT with residual bending is larger than that of straight CT. As for the two initial trigonometric shapes, the sinusoidal critical buckling force of these two initial modes is almost the same, but CT with initial cosine mode tends to buckle easier than CT with initial sine mode in helical buckling. To verify the proposed model, the results of this paper are compared to Saliés's experimental results, which support the proposed solutions. The comparison between buckling solutions of CT with residual bending and CT without residual bending show that the effect of residual bending on CT cannot be ignored in buckling analysis.

1. Introduction

The buckling behavior of tubular has been studied for more than half centuries. Lubinski (1950, Lubinski and Althouse, 1962) first systematically analyzed the 2D lateral buckling and 3D helical buckling of drill string in vertical wells, and derived the relationship between the critical axial force and the pitch of helix with energy method. Paslay and Bogy (1964) and Dawson and Paslay (1984) derived the first, now well-known, expression (Eq. (1)) for the critical sinusoidal buckling load of a tubular constrained in an inclined wellbore.

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

Where F_{crs} is the critical sinusoidal buckling load, q is the tubular weight per unit length, α is the inclination angle of a wellbore, EI is the bending stiffness, r_c is the radial clearance between tubular and a wellbore.

Mitchell (1988) established the buckling equation and the contact force describing a pipe constrained in an inclined wellbore.

$$EIr_c\left[\frac{d^4\theta}{dz^4} - 6\left(\frac{d\theta}{dz}\right)^2\frac{d^2\theta}{dz^2}\right] + r_c\frac{d}{dz}\left(F\frac{d\theta}{dz}\right) + q\sin\alpha\sin\theta = 0$$

$$N = EIr_c\left[4\frac{d\theta}{dz}\frac{d^3\theta}{dz^3} + 3\left(\frac{d^2\theta}{dz^2}\right)^2 - \left(\frac{d\theta}{dz}\right)^4\right] + Fr_c\left(\frac{d\theta}{dz}\right)^2 + q\sin\alpha\cos\theta$$

Where θ is the angular displacement, N is the normal contact force.

From then on many researchers found the same formula with that derived by Paslay for critical sinusoidal buckling force. However, this sinusoidal buckling force is the critical point between the initial straight configuration and sinusoidal configuration. This means when the axial force is less than the critical sinusoidal buckling force, CT will remain in straight configuration. As the axial force increases further, Miska et al. (1996) noticed the phenomenon that the sinusoidal configuration will change from a stable snaking shape into an unstable snaking shape (transition shape), and

* Corresponding author.
E-mail address: qin99xing@163.com (X. Qin).

http://dx.doi.org/10.1016/j.jngse.2016.02.016
1875-5100/

eventually into a helical configuration. Finally he derived the critical force from stable snaking configuration to unstable snaking configuration. Mitchell (1997) also pointed out the transition from lateral buckling to helical buckling and had given the critical transition force. As for the complete helical configuration, Chen et al. (1990) presented a study for pipe buckling in horizontal wells and derived an equation for the critical helical buckling force. In the next few decades, Gao et al. (1998), Gao (2006), Gao and Huang (2015), Liu (1999) and Huang et al. (2015) studied buckling behaviors by using both the energy method and the tubular-buckling equations. The values of critical buckling loads proposed by the above researchers are given in Table 1.

However, these models typically assumed that the tubular was initially straight in the wellbore. This assumption is suitable for tubulars like dill pipe, tubing, casing and so on, but for coiled tubing (CT). Actually every CT has minor initial bending. After a coiled tubing string is manufactured, it is plastically bent around a reel and then transported to every well site. During operations, the CT is unspooled from the reel and bent on the gooseneck and then sent into the injector. As the CT goes through the injector, the gripping block will crush on CT to inject it into the wellbore. Throughout the process (shown in Fig. 1), CT goes through four times bending-straighten deformation, and every bending deformation makes the CT into plastic state resulting in residual bending. After entering into the wellbore, the CT is not straight but has an initial configuration. This initial configuration is caused by residual bending.

As to our knowledge, only several studies considered the effect of residual bending. Miska et al. (1996) observed the effect of residual bending on pipe in experiment. A pipe with residual bending behaves more flexible than straight pipe and consequently less efficient for axial force transfer. Qiu et al. (1997, 1999) established a new model to analyze the effect of CT initial configuration on sinusoidal and helical buckling behavior in deviated and curved wells with the energy method. They assumed the initial configuration of CT was sinusoidal and concluded that the initial configuration had an essential effect on the axial force to produce a helical configuration. Zheng and Adnan (2005) also noticed the questions of residual bending in CT, and he assumed that the initial configuration of CT was in the form of a helix. However, we think the initial helical configuration may not correspond to actual situation.

In this paper, the initial configuration of CT is not just in one configuration but in two typical trigonometric shapes: sine mode or cosine mode. By using the beam-column method, new governing differential equations are derived for predicting the sinusoidal and helical buckling behaviors of CT with residual bending in a horizontal well. The maximum bending moment, axial compressive displacement and contact force between the CT and wellbore are also calculated. When the initial configuration of CT is straight, buckling solutions of the new equations are identical with previous conventional results. Through these analyses, we can see the significant effect of CT initial disturbance on the buckling behavior. These new results allow for accurate job design to operate CT in the wellbore.

Table 1
The values (F/F_{crs}) of critical buckling loads for different buckling models.

Researchers	Straight	Sinusoid	Transition	Helix
Chen et al (1990)	[0, 1]	$[1, \sqrt{2}]$	/	$[\sqrt{2}, \infty]$
Miska et al. (1996)	[0, 1]	[1, 1.875]	$[1.875, 2\sqrt{2}]$	$[2\sqrt{2}, \infty]$
Mitchell (1997)	[0, 1]	$[1, \sqrt{2}]$	$[\sqrt{2}, 2\sqrt{2}]$	$[2\sqrt{2}, \infty]$
Gao et al. (1998)	[0, 1]	[1, 1.401]	/	$[1.401, \infty]$

2. CT buckling equation

2.1. Major assumption

In order to build the tubular analysis model, we take following major assumptions:

1 The wellbore is a horizontal straight cylinder.
2 The CT is in continuous contact with the wellbore.
3 The slender-beam theory is used to relate bending moment to curvature.
4 Friction force between the tubing and wellbore is neglected.
5 The initial amplitude of CT angular displacement is small.

2.2. Geometric description

The O-xyz coordinate is shown in Fig. 2. The origin of the Cartesian coordinates is set at the center of the cross section of the wellbore at the leftmost end. The z axis points horizontally from left to right along the axis of the wellbore. The x axis points vertically downward, and the y axis is perpendicular to the x-z plane.

Fig. 3 illustrates the initial configuration of a CT with residual bending that is subjected to no axial load from top view and front view. It is assumed that inside the wellbore, the CT lies on the lower side of the wellbore as a result of gravity. The initial position of a point on the axis of the CT is denoted by $C_0(x_0, y_0, z_0)$, where x_0, y_0 are the initial lateral displacements of CT with residual bending, as shown in Fig. 3.

$$x_0 = r_c \cos \theta_0 \tag{2}$$

$$y_0 = r_c \sin \theta_0 \tag{3}$$

Where θ_0 is the initial angular displacement, and r_c is the radial clearance between CT and the wellbore.

Now an axial compressive load is applied on the left end of the tubing. As shown in Figs. 4 and 5, the point originally located at $C_0(x_0, y_0, z_0)$ will move to $C(x, y, z)$.

$$x = r_c \cos \theta \tag{4}$$

$$y = r_c \sin \theta \tag{5}$$

Where x, y are the final lateral displacements, and θ is the final angular displacement.

2.3. Equilibrium equations

The tubular-buckling equation and the wellbore contact force considering the initial configuration in a horizontal well are as follows. The process of building the buckling equation is shown in Appendix A.

$$EIr_c\left[\frac{d^4\theta}{dz^4} - 6\left(\frac{d\theta}{dz}\right)^2\frac{d^2\theta}{dz^2}\right] + r_cF\frac{d^2\theta}{dz^2} + q\sin\theta + EIr_c(C_3\sin\theta - C_4\cos\theta) = 0 \tag{6}$$