Journal of Petroleum Science and Engineering 152 (2017) 182–192

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

# Inter-helical and intra-helical buckling analyses of tubular strings with connectors in horizontal wellbores

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ARTICLE INFO

*Keywords:*
Tubular mechanics
Helical buckling
Connector
Contact force
Bending moment

ABSTRACT

Helical buckling of tubular strings with connectors is divided into two sub-problems: inter-helical buckling and intra-helical buckling. The suspended section of the tubular string is depicted by beam-column model and the continuous contact section is depicted by helix. Further introducing the continuous conditions, boundary conditions and periodic conditions, the deflection curves of tubular strings can be determined. On the basis of energy stability condition, the critical helical buckling loads are deduced by introducing the potential energy factor. The contact forces on contact points and continuous contact sections and maximum bending moments on tubular strings are calculated. The above studied are further applied into a case study. At last, the supporting effect and boundary effect caused by connectors are introduced and the relationship between inter-helical buckling and intra-helical buckling modes is clarified. The results indicate that for connectors of smaller diameters, the supporting effect plays the most important role and inter-helical buckling is easier to initiate. However, for connectors of larger diameters, the constraint effect is dominant and intra-helical buckling is more likely to occur. Increasing connector diameter and decreasing the length between adjacent connectors can increase critical helical buckling loads. Both the contact forces and maximum bending moments in the intra-helical buckling mode are larger than that in the inter-helical buckling mode, so intra-helical buckling should be avoided in the optimal design of connectors on tubular strings.

## 1. Introduction

Until now, many researchers have conducted a series of studies on the lateral buckling, sinusoidal buckling and helical buckling behaviors of tubular strings constrained in vertical, inclined (horizontal) and curved wellbores with energy method and buckling differential equation (Lubinski 1950, 1962; Paslay 1964; Mitchell 1982, 1988, 1999, 2002; Chen 1990; Gao 1998, 2002, 2006, 2013; Gao 2009, 2010; Miska 1995; Wu 1992, 1995; Huang 2015a, 2015b) and a mature theoretical framework of tubular buckling has been established. In the above studies, the entire tubular string is taken as a uniformly smooth rod and the effects of connectors on tubular strings are neglected. Lubinski (1977) and Paslay and Cernocky (1991) studied the lateral deflection of a weightless tubular string under axial tension and compression constrained in a curved wellbore. Gao et al. (2012) studied the critical lateral buckling condition for a tubular string constrained in a horizontal wellbore. On the basis of Paslay and Gao's results, Huang (2015d) studied the lateral buckling for a tubular string with weight constrained in a curved wellbore. (Mitchell, 2000, 2003a,b) studied the helical buckling of the tubular string with connectors in no contact case in vertical wellbores and the sinusoidal buckling in no contact case in inclined and curved wellbores. Huang and Gao (2014a, 2014b, 2015), Huang et al. (2015c, 2016) extended Mitchell's work and studied the sinusoidal buckling and helical buckling under three contact cases in vertical, horizontal and curved wellbores.

However, the previous mechanical analyses on tubular strings with connectors are not mature, since the critical buckling loads, contact forces and maximum bending moments for different buckling modes have not been deduced. Meanwhile, the coupling effects of connector and buckling are not sufficiently revealed. Especially for the helical buckling problem, connectors have two different kinds of effects and lead to two kinds of helical buckling modes, which have not been concerned in the previous studies. In this paper, the inter-helical buckling and intra-helical buckling problems are studied. The critical buckling loads, contact forces and maximum bending moments are deduced by mechanical analysis. The supporting effect and boundary effect caused by connectors are introduced and the relationship between inter-helical buckling and intra-helical buckling modes is clarified.

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http://dx.doi.org/10.1016/j.petrol.2017.03.004
Received 15 October 2015; Received in revised form 1 March 2017; Accepted 1 March 2017
Available online 02 March 2017
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## 2. Inter-helical buckling of tubular strings with connectors

Two kinds of helical buckling including inter-helical buckling and intra-helical buckling are discussed. Inter-helical buckling means that the an whole buckling configuration occurs across several adjacent connectors, while intra-helical buckling means that helical buckling only happens on a portion of the tubular string between adjacent connectors. The investigation in these two helical buckling problems is based on the following assumptions:

1. The tubular string is taken as a thin rod and the horizontal wellbore as an ideal horizontal cylinder.
2. The tubular string deflection is a small term with respect to the tubular string length and in elastic range.
3. Connectors are evenly distributed along the tubular string and in contact with the inner surface of the wellbore.
4. Every portion of the tubular string between two adjacent connectors has the same deflection curve.
5. Friction and torque are neglected.

### 2.1. Critical buckling loads

Assuming that x and y are the lateral displacements along x-axis and y-axis, z is the axial distance along z-axis shown in Fig. 1, the potential energy of tubular string caused by axial force and bending moment is calculated by ((Gao, 2006))

$$\Pi_p = \frac{EI}{2}\int_0^L\left[\left(\frac{\partial^2 x}{\partial z^2}\right)^2+\left(\frac{\partial^2 y}{\partial \eta^2}\right)^2\right]dz-\frac{F}{2}\int_0^L\left[\left(\frac{\partial \hat{x}}{\partial \eta}\right)^2+\left(\frac{\partial \hat{y}}{\partial \eta}\right)^2\right]dz$$
$$=\frac{EIr_c^2}{2L^3}\left\{\int_0^1\left[\left(\frac{\partial^2 \hat{x}}{\partial \eta^2}\right)^2+\left(\frac{\partial^2 \hat{y}}{\partial \eta^2}\right)^2\right]-u^2\left[\left(\frac{\partial \hat{x}}{\partial \eta}\right)^2+\left(\frac{\partial \hat{y}}{\partial \eta}\right)^2\right]d\eta\right\} \tag{1}$$

Where η is the dimensionless distance equal to z/L, L is the length of tubular strings between adjacent connectors, $\hat{x}$ and $\hat{y}$ are the dimensionless lateral displacements calculated by $\hat{x}=\frac{x}{r_c}$ and $\hat{y}=\frac{y}{r_c}$, $r_c$ is the radial clearance between the connector and wellbore, and u is the dimensionless axial compression defined by $u=\sqrt{\frac{F}{EI}}\cdot L$, F is the axial compression, EI is the bending stiffness of the tubular string.

For the non-connector case, the deflection curve of the tubular string is $\hat{x}=\delta_b\sin\left(\frac{u}{\sqrt{2}}\eta\right)$ and $\hat{y}=\cos\delta_b\left(\frac{u}{\sqrt{2}}\eta\right)$ ((Lubinski and Althouse, 1962)), where the term $\delta_b=\frac{r_b}{r_c}$ is the ratio of the radial clearance between tubular string body and wellbore ($r_b$) to that between the connectors and wellbore ($r_c$), Eq. (1) is simplified into

$$\Pi_p^0=\frac{EIr_c^2}{2L^3}\cdot\left(-\frac{u^4\delta_b^2}{4}\right) \tag{2}$$

The potential energy factor is defined by the ratio of Eq. (1) to Eq. (2), namely

$$\lambda_{\pi,p}=\frac{\Pi_p}{\Pi_p{}^0}=-\frac{4}{u^4\delta_b^2}\left\{\int_0^1\left[\left(\frac{\partial^2 \hat{x}}{\partial \eta^2}\right)^2+\left(\frac{\partial^2 \hat{y}}{\partial \eta^2}\right)^2\right]-u^2\left[\left(\frac{\partial \hat{x}}{\partial \eta}\right)^2+\left(\frac{\partial \hat{y}}{\partial \eta}\right)^2\right]d\eta\right\} \tag{3}$$

The detailed calculation procedures of deflection curves of tubular strings with connectors under different contact cases are given in Appendix A. The results indicate that the tubular strings go through no contact, point contact and wrap contact with the increase of axial compressions. Substituting the expressions of $\hat{x}$ and $\hat{y}$ into Eq. (3), the value of potential energy factor is determined.

If the potential energy due to tubular gravity is further considered, the total potential energy change is calculated by

$$\Pi_t=\Pi_p+\Pi_g$$
$$=\frac{EIr_c^2}{2L^3}\left\{\int_0^1\left[\left(\frac{\partial^2 \hat{x}}{\partial \eta^2}\right)^2+\left(\frac{\partial^2 \hat{y}}{\partial \eta^2}\right)^2\right]-u^2\left[\left(\frac{\partial \hat{x}}{\partial \eta}\right)^2+\left(\frac{\partial \hat{y}}{\partial \eta}\right)^2\right]d\eta\right\}+qr_bL$$
$$=\lambda_{\pi,p}\cdot\left\{\frac{EIr_b^2}{2L^3}\cdot\int_0^1\left[\left(\frac{\partial^2 \hat{x}^0}{\partial \eta^2}\right)^2+\left(\frac{\partial^2 \hat{y}^0}{\partial \eta^2}\right)^2\right]-\frac{Fr_b^2}{2L}\cdot\left[\left(\frac{\partial \hat{x}^0}{\partial \eta}\right)^2+\left(\frac{\partial \hat{y}^0}{\partial \eta}\right)^2\right]d\eta\right\}+qr_bL$$
$$=\frac{(\lambda_{\pi,p}\cdot EI)\cdot r_b^2}{2L^3}\cdot\int_0^1\left[\left(\frac{\partial^2 \hat{x}^0}{\partial \eta^2}\right)^2+\left(\frac{\partial^2 \hat{y}^0}{\partial \eta^2}\right)^2\right]-\frac{(\lambda_{\pi,p}\cdot F)\cdot r_b^2}{2L}\cdot\left[\left(\frac{\partial \hat{x}^0}{\partial \eta}\right)^2+\left(\frac{\partial \hat{y}^0}{\partial \eta}\right)^2\right]d\eta+qr_bL \tag{4}$$

In which $\Pi_g$ is the potential energy due to tubular gravity, the superscript ° represents the results in the no connector case. Note that the dimensionless potential energy Eq. (3) is adopted in the derivation of Eq. (4).

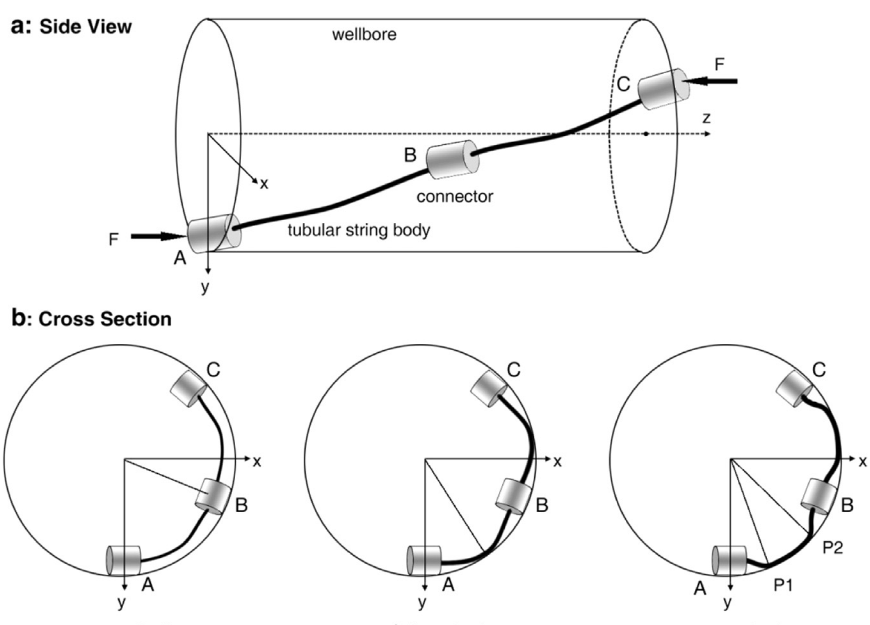


**Fig. 1.** Schematic of helical buckling of a tubular string with connectors constrained in a horizontal wellbore: (a) no contact (b) point contact (c) wrap contact.

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