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Local mechanical model of down-hole tubular strings constrained in curved wellbores

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ABSTRACT

Kinds of tubular strings are widely applied to the development of oil and gas fields. Most of these tubular strings constrained in straight or curved wellbores can be taken as homogeneous thin elastic rods constrained in straight cylinders or tori. Recent studies have shown that connectors on the tubular strings play an important role on the tubular string deflection problem. On the basis of previous studies, this paper provides a new model to describe the deflection behaviors of a tubular string with connectors constrained in a curved wellbore. The axial force on the ends of the tubular string is divided into axial tension and axial compression. The deflection state is divided into no contact, point contact and wrap contact according to the radial displacement of the tubular string or divided into initial configuration, sinusoidal buckling and helical buckling configurations according to the angular displacement of the tubular string. The critical conditions between no contact and point contact, between point contact and wrap contact in the initial configuration are studied. The deflection curves under the three contact cases in the initial configuration are obtained. These results show that the deflections curves and critical conditions are closely related to the tubular string weight and wellbore curvature. The effects of tubular string weight, wellbore curvature, connectors and axial force on bending moment and contact force are also analyzed at last.

1. Introduction

Drilling mechanics is the most important theoretical basis of directional drilling theories and control techniques, in which down-hole tubular string mechanics is the most classic part. Since Lubinski's (1950) pioneering work on the buckling of rotary drilling string, a lot of achievements about down-hole tubular string mechanics have been made and published. Up to now, new insights enrich this field continually.

The tubular string mechanics is mainly divided into two categories: global mechanical model and local mechanical model. The global mechanical model means that the whole down-hole tubular string is taken as the research object. The global model is referred to the torque & drag model, in which soft rope (Brett et al., 1989; Johancsik et al., 1984) and stiff rod (Gao, 1994; Ho, 1988) models are the most mature. In the global mechanical model, two assumptions are usually introduced (Gao, 1994): (1) the axis of the tubular string is identical with that of the wellbore and (2) the tubular string is in continuous contact with the wellbore. However, these two assumptions are too idealistic to be satisfied in practice. The existence of connectors on the tubular string makes some parts of the tubular string lose contact with the wellbore and the axis of the tubular string deviate from that of the wellbore. So the global model roughly depicts the deflection behaviors of the down-hole tubular string from a whole aspect. In order to obtain a more detailed description of the tubular string deformation, the local mechanical model is introduced.

The local mechanical model means that only a local part of the tubular string is in consideration. The core of local mechanical model is to study the deflection of a tubular string under the combined effects of tubular string weight, buckling, connector and wellbore constraint. The local mechanical model is roughly divided into two categories according to the specific engineering objectives. One is used to predict the well trajectory also called bottom-hole-assembly (BHA) model (Bai and Su, 1990; Gao, 1994; Millheim et al., 1978), the other is used to calculate the bending stress concentration and contact force on the tubular string which is closely related to the tubular string failure problem (Lubinski, 1977). Here, we focus on the latter part of the local mechanical model.

To study the tubular string failure, kinds of external loads applied on the tubular string should be obtained in advance. The global mechanical model mainly provides the axial force, torque and distributed contact force applied on the tubular string. However, the external loads may be underestimated only with the global model results, since the bending stress concentration and

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concentrated contact force exist on the tubular string due to the effect of the connectors on the tubular string. To overcome this problem, the local mechanical model provides a more reasonable estimation of external loads.

In the local mechanical model, connectors are usually assumed to distribute discretely along the tubular string and the diameters of connectors are larger than that of the tubular string body. So there are three contact cases between the tubular string and the wellbore (Lubinski, 1977), namely no contact (N), point contact (P) and wrap contact (W). No contact means that the tubular string suspends between connectors and is not in contact with the wellbore; point contact means that the tubular string is in contact with the wellbore at a single point; wrap contact means that a segment of the tubular string is in continuous contact with the wellbore. Here, the no contact, point contact and wrap contact are defined from the view of radial displacement of the tubular string. Another deflection classification called buckling state is based on the angular displacement of the tubular string (Hajianmaleki and Daily, 2014), namely the initial configuration (I), sinusoidal buckling (S) and helical buckling configurations (H). A tubular string with connectors lies on the bottom of the wellbore when the axial compression is rather small. When the axial compression exceeds specific values, the tubular string becomes unstable and buckles in a sinusoidal configuration in which the tubular string snakes along the lower surface of the wellbore or even a helical buckling configuration in which the tubular string forms a helix spiraling around the inner surface of the wellbore. Here we define the deflection state as the combination of contact state and buckling state. Therefore, there are nine kinds of deflection states, namely "I&N", "I&P", "I&W", "S&N", "S&P", "S&W", "H&N", "H&P" and "H&W". There are twelve kinds of critical conditions between different deflection states, namely "C_{IS_N}", "C_{SH_N}", "C_{IS_P}", "C_{SH_P}", "C_{IS_W}", "C_{SH_W}", "C_{NP_I}", "C_{PW_I}", "C_{NP_S}", "C_{PW_S}", "C_{NP_H}" and "C_{PW_H}". The relationship between the deflection states and critical conditions are shown in Fig. 1.

Up to now, several papers about the local mechanical model have been published. Lubinski (1977) studied the deflection of a weightless tubular string in axial tension constrained in a curved wellbore under the case of "I&N" to "I&W". Later, Paslay and Cernocky (1991) extended Lubinski's (1977) work to the case of axial compression. Mitchell and Stefan (2006a, 2006b) studied the deflection behavior of a weightless tubular string constrained in a straight wellbore under the case of "H&N". Huang and Gao (2014a) extended Mitchell's work and studied the case of "H&N" to "H&W".

However, the weight of the tubular string cannot be neglected in practice. Mitchell (2003a,b) studied the deflection behavior of a tubular string with weight constrained in straight and curved wellbores under the case of "I&N" to "S&N". Gao et al. (2012) studied the case of "I&N" to "I&W" in a straight wellbore. Huang and Gao (2014b) extended Mitchell's (2003b) work to the case of "I&N" to "S&W" in a straight wellbore.

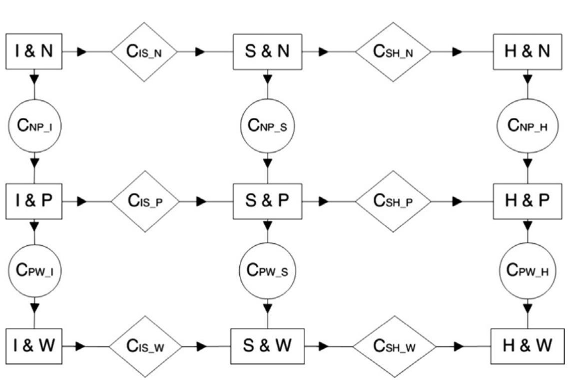

Fig. 1. Phase diagram of deflection states and critical conditions.

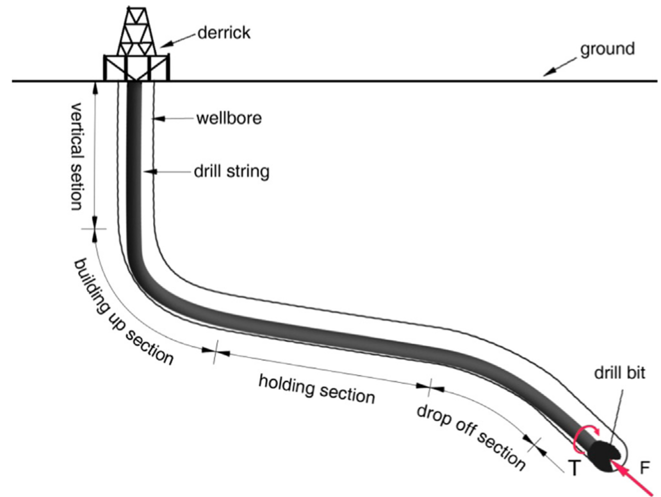

Fig. 2. Drill string constrained in the horizontal well

From the above achievements we can see that the deflection of a tubular string with weight constrained in a curved wellbore for the case of "H&N" and "I&P" to "H&W" is still need to study. Considering that buckling generally does not occur in a curved wellbore, "I&N" to "I&W" in curved wellbores is our main research objective.

In this paper, the deflection model of a tubular string with weight in a curved wellbore for the case of "I&N" to "I&W" is built. The new model considers no contact, point contact and wrap contact cases for axial tension and compression, which also can be seen as the extension of Lubinski (1977), Paslay and Cernocky, (1991) and Gao et al. (2012)'s studies. The critical conditions between different contact cases and the deflection curves under different contact cases are given. The bending moment and contact force on the tubular string are analyzed.

2. Backgrounds

Fig. 2 is the schematic of the drill string constrained in a typical directional well. The whole well is divided into vertical, building up, holding, drop off sections, and so on. In the drilling process, the drill bit continually breaks the front rocks, and meanwhile a slender hole called wellbore is drilled. The wellbores in the vertical and holding sections are taken as straight cylinders, while the wellbores in the building up and drop off sections are seen as tori. A drill string constrained in the wellbore connects the ground equipment and drill bit. The deflection behaviors of the drill string can be obtained by the deflection model of a thin elastic rod constrained in a cylinder or torus.

Fig. 3 shows the three contact cases of a weightless tubular string with axial tension and axial compression on its ends constrained curved wellbores. When the axial force is zero, the axis of the tubular string is an arc which is parallel to the axis of the wellbore. When the axial force is a tension, the connectors touch the inner circle of the wellbore, and meanwhile the axis of the tubular string deviates from the initial arc configuration and tends to touch the inner circle of the wellbore. With the increase of axial tension, the tubular string goes through no contact, point contact and wrap contact. Note that the outer circle of the wellbore does not affect the deflection of the tubular string in axial tension case. However, when the axial force is a compression, the connectors touch the outer circle of the wellbore, and meanwhile the axis of the tubular string deviates from the initial arc configuration and tends to touch the outer circle of the wellbore. Similarly, the inner circle of the wellbore has no effect on the deflection of the tubular