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Computer simulation of resistance force mitigation through curvature bridging in extended bore-holes

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ABSTRACT

As is shown in scientific literature, the curvature discontinuity of a bore-hole trajectory can be one of the most influential factors in generation of friction forces resisting to motion of drill strings. To avoid the curvature discontinuities between the bore-hole sections, curvature-bridge curves in the shape of clothoid spirals were proposed for their smoothing. In this paper, it is shown that if the transient clothoid curve is short, the cubic parabola bridge can be substituted for it. As demonstrated below with the use of the elaborated stiff string drag and torque model, this curve has simpler geometry and is suitable for use of spline approximations. The impact of the curvature break smoothing on the resistance forces reduction is investigated for tripping in and out operations and different regimes, simulating drilling procedure. The cases of pure sliding, pure rotation and their combinations are considered for the 2D and 3D models of the bore-hole trajectories.

1. Introduction

The problem of design of curvilinear trajectories as combinations of simplest curve segments has important applications in engineering. It is conceivable that the most important and illustrative questions of this direction are related to the transport technology, namely, in the design of track trajectories. If a vehicle traveling on a rectilinear road instantly proceeds to a tangential circumferential track, it undergoes an instantaneous centripetal acceleration starting at the interface point, and thus, a generated centrifugal inertia force begins instantly to act causing a shock.

With enlargement of speeds of the automobiles and rail vehicles, the impact effects at the tangent points of track junctions are made more detrimental and it becomes evident that their mitigation should be accomplished in such a way as to prevent discontinuities of the track curvatures and to avoid the shock phenomena. This aim is attained through insertion of a transition section at the interface point between the track segments with different curvatures. It was acknowledged that the clothoid curve was the most suitable for this purpose. To reduce friction forces acting on a drill string in a sectional bore-hole, Samuel (2008, 2010) proposed to use the clothoid curvature bridging for extended reach drilling.

Clothoid (Cornu's spiral) is a line (Fig. 1) whose curvature changes linearly with its length variation. This principle defines the transition geometry between rectilinear and circular curves:

- the clothoid curvature begins with zero at the straight section (at the tangent point) and increases linearly with its curve length;
- at the point where the clothoid meets (touches) the circular curve, its curvature becomes equal to curvature of the latter.

The clothoid outline is represented in the integral form (Abramowitz and Stegun, 1972):

$$x(s) = \int_0^s \cos\left[(as)^2\right] ds, \quad y(s) = \int_0^s \sin\left[(as)^2\right] ds \tag{1}$$

where, x, y are the coordinates of the curve points; s is the natural parameter; $a = 1/\sqrt{2R_c s_c}$ is the constant; R_c and s_c are, correspondingly, radius and length values at any prescribed point of the curve.

Let the clothoid curvature $k = k_c$ be known at its point $s = s_c$ ($s_c \neq 0$). Then, on the basis of condition $a = const$, it can be calculated throughout the curve length

$$k(s) = \frac{k_c \cdot s}{s_c} \tag{2}$$

In a similar manner, taking into account that curvature k and angle θ of the curve tangent inclination are tied by differential correlation

$$k = ds/d\theta, \tag{3}$$

the equality

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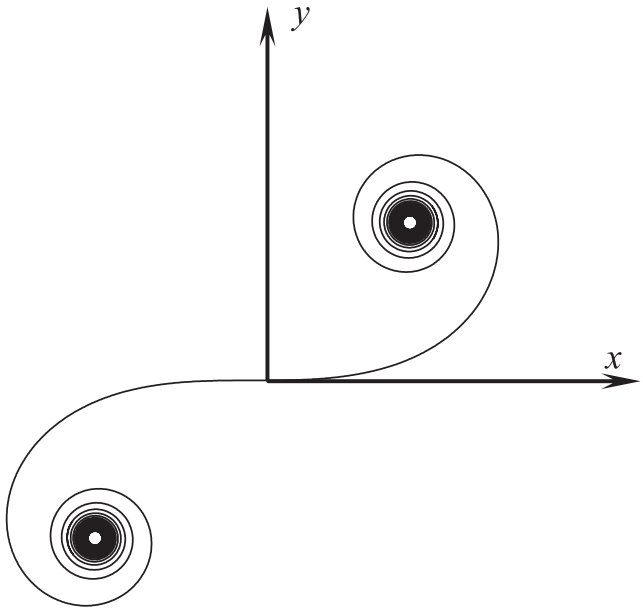

Fig. 1. Clothoid curve used in railway transport for rail segments joining.

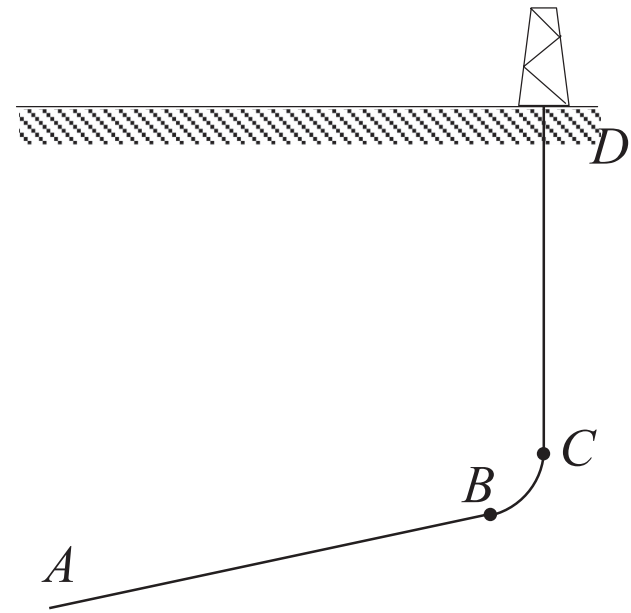

Fig. 2. Multilink trajectory of a bore-hole.

$$\theta = (a\,s)^2 \tag{4}$$

can be deduced.

To complete the statement of the problem of geometric transition from a straight line to a circle without discontinuity of the track curvature, write down also the formulae for the coordinates of the curve center at its point $x(s)$, $y(s)$ (Abramowitz and Stegun, 1972)

$$x_c = x - \frac{y'\left[(x')^2 + (y')^2\right]}{\begin{vmatrix} x' & y' \\ x'' & y'' \end{vmatrix}}, \quad y_c = y + \frac{x'\left[(x')^2 + (y')^2\right]}{\begin{vmatrix} x' & y' \\ x'' & y'' \end{vmatrix}} \tag{5}$$

where, the prime symbol denotes differentiation with respect to s.

These relationships are usually represented in the simplified way

$$x_c = x - R dy/ds, \quad y_c = y + R dx/ds. \tag{6}$$

The outlined clothoid sections (though not simple) are now widely used in rail and highway engineering for providing transitions between horizontal segments of tracks with different curvatures. If the track transition experiences small angular changes, the clothoid curve can be approximated by cubic parabola whose curvature changes also smoothly, starting from zero value.

Analogous problem appears also in the technology of curvilinear bore-hole drilling associated with extraction of oil and gas fuels from deep and extended-reach deposits, though, in our opinion, it is solved only on the basis of geometric analysis of the bore-hole trajectory without paying appropriate attention to mechanical aspects of the accompanying phenomena. Namely, in the practice of design of the directed bore-holes, the method of minimal curvature is in wide use. In accordance with it, the bore-hole trajectory is represented as a combination of several rectilinear sections joined to one another by circumference arcs so that the angle of the inclination of the tangent to the bore-hole axis changes continuously (sections *AB*, *BC*, and *CD* in Fig. 2). But in so doing, the bore-hole axis line curvature (as well as the DS axis curvature and the elastic bending moment) turns out to be discontinuous resulting in local enlargement of contact force interaction between the DS and bore-hole wall.

It was detected by in situ observations that the bore-hole geometry exerted essential influence on the friction forces acting on the drill string in its dragging. Generally, this friction determines the maximum horizontal length that can be achieved before lock-up or lateral buckling of the DS. So, the problem of friction forces reduction through the rational choice of a bore-hole path was the subject of wide scientific discussions (Aadnoy and Andersen, 2001; Choe et al., 2005; Gulyayev and Andrusenko, 2013; Gulyayev et al., 2011, 2015; Johancsik et al., 1984; Sheppard et al., 1987).

To assess the friction effects connected with different bore-hole outlines, soft (zero-moment) drill-and-torque model based on the theory of flexible cable was elaborated. On its basis, modeling of these effects has been primarily initiated by Johancsik et al. (1984) and subsequently set for a standard differential form by Sheppard et al. (1987). With the use of this approach, the minimum curvature method was substantiated (Aadnoy and Andersen, 2001; Choe et al., 2005; Johancsik et al., 1984; Lyons et al., 2016; Sawaryn and Thorogood, 2005; Sheppard et al., 1987). Yet, the hypothesis for momentless DS can cause essential faults in calculation of contact and friction forces in the vicinity of interface points on the bore-hole axis.

These factors may be responsible for some negative features of the drilling process:

- they can provoke redistribution of external and internal forces providing basic cause of deterioration of the DS mobility in the bore-hole cavity entailing decrease of the WOB (weight on bit) and TOB (torque on bit) permeability to the bore-hole bottom and reducing the drilling efficiency;
- additional friction forces can bring to reduction of axial tensile forces (stabilizing the DS tube) and enlargement of longitudinal compressive forces, triggering the DS buckling;
- they result in more intensive wear and tear of drilling equipment;
- the generated zones of increased contact and friction forces can be also responsible for dead or locked states of the DSs.

Mitigation of these effects can be achieved through the use of the trajectory curvature bridging by clothoid sections (Samuel, 2008, 2010).

Below, confirmation of this assertion is performed with the use of the elaborated 3D stiff string drag and torque model. It is based on the theory of curvilinear flexible rods described in papers Gulyayev and Andrusenko (2013), Gulyayev et al. (2011, 2015). Previously, it was used for research of the friction forces, resisting to motion of the DS inside the bore-holes with 3D geometric imperfections (spiral wavelets and 3D “dog leg breaks”). It was found that above all, the resistance forces were

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