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Dynamic buckling with friction inside directional wells

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ABSTRACT

The construction of deep and directional offshore wells brought the necessity to understand the behavior of columns on such conditions. Completely understanding their behavior means to be able to design and operate them while avoiding any problems. In the present work, we studied the differences observed on the measurements of the friction force during operations of tripping in and tripping out a tubing, one of the problems associated to columns inside directional wells. It is worth noting that this problem can occur in various operations, such as lowering a sand screen curled on a pipe inside an open hole segment, lowering a tubing string inside a casing string, or lowering a coiled tubing inside a tubing string. Generally, the projects – and even commercial software – consider only the associated static problem, which proved itself as not being able to justify the measurement differences obtained on field. Therefore, the present work introduces a dynamic model in opposition to the static model to explain the mentioned phenomenon. The main hypothesis is that the column buckling inside the well would cause it to vibrate differently during tripping in and tripping out. During tripping in, the column is under compression and thus suffers buckling, displacing itself angularly inside the well to either form a sinusoid or a helix; meanwhile, during tripping out, the column is under tension and thus there is no buckling, meaning that the column will remain in contact with the shortest portion of the well the whole time. Using the models developed to characterize the column during tripping in and out, it was observed that, in fact, the friction force is different on both cases, thus proving the hypothesis that buckling is the responsible for the observed differences on hook load during operations of tripping in and out a column.

1. Introduction

Since the technology of directional drilling was improved on the USA in the 70s, directional wells became the reality of the oil industry. In Brazil, the first directional wells were drilled in the 80s, while the first horizontal wells were drilled on the 90s. As the years passed, the percentage of directional and horizontal wells relative to the total wells kept increasing. This happened due to innumerous advantages that directional wells have over vertical ones, such as increasing the well productivity by increasing the area in contact with the reservoir. Directional drilling became pretty much the standard way of constructing a well for offshore environments, as can be seen on ANP (2012), in which the basins with the highest percentages of directional wells are the ones located offshore. Aside from increasing the productivity, directional wells have a number of different applications (Bourgoyne et al., 1986; Rocha et al., 2006) such as developing several wells from a single platform, reaching hard objectives, sidetracking, exploring fractured reservoirs and relieving other wells to control blowouts. Therefore, directional wells are extremely important for the oil industry and understanding the behavior of all the equipment during operations of directional drilling becomes vital to ensure safety. The present work focuses on the dynamic behavior of columns used on completion operations inside a directional well. During completion – and, by extension, on well interventions – several operations involve the use of a column inside another column, such as lowering a tubing string inside a cased hole; a coiled tubing string inside a tubing string; or a sand screen using a work string inside an open hole. Thus, these columns will be free to vibrate during such operations while being constrained by the well or another column; these vibrations are the object of study of the present work.

On the aforementioned operations, it was observed that the friction on the column – measured indirectly through the hook load – was different during operations of tripping in and out inside the well. This problem originally appeared when measurements of hook load during tripping in and out – which were taken since the auxiliary lines from the tubing were failing – indicated that the friction force would be different in both cases. This was unexpected because none of the current models and software can explain this effect or even consider

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Nomenclature

A	cross sectional area, m^2
C_f	friction coefficient
dx	infinitesimal element of length, m
E	Young's modulus, Pa
f	total dynamic friction coefficient
f_1	dynamic friction coefficient on the axial direction
f_2	dynamic friction coefficient on the tangential direction
$\vec{F}(x)$	axial compressive force, N
$\vec{F_f}$	total friction force, N/m
$\vec{F}_{f1}$	friction force component on the axial direction, N/m
$\vec{F}_{f2}$	friction force component on the tangential direction, N/m
F_x	axial internal force, N
g	gravitational acceleration, m/s^2
$\hat{i}$	axial direction vector (direction vector on x axis)
I	area moment of inertia, m^4
I_p	mass moment of inertia, kg*m^2
$\hat{j}$	direction vector on y axis
$\hat{k}$	direction vector on z axis
L	column length, m
m_p	mass per unit of length, kg/m
N	normal contact force per unit of length, N/m
$\hat{p}$	normal direction vector
$\hat{q}$	tangential direction vector
r	clearance between the column and the well, m
t	time variable, s
$u(x,t)$	axial displacement function, m
u_a	axial displacement due to axial tension/compression, m
u_b	axial displacement due to bending, m
u_x	total axial displacement, m
U_h	heave amplitude, m
v_1	velocity on the axial direction, m/s
v_2	velocity on the tangential direction, m/s
x	space coordinate on the axial direction, m
α	well inclination angle
θ	angular displacement, rad
ω	column rotational angular frequency, rad/s
ω_h	heave angular frequency, rad/s

that the column can have different friction forces. Since this phenomenon did not happen with drill strings – which are stiffer than tubings and coiled tubings – the cause would probably be associated with buckling. During tripping in, the tubing is being pushed inside the well, thus a compressive force acts on both ends due to the reaction of the wellbore; meanwhile, during tripping out, the tubing is being pulled from the well, thus a tension force is applied instead. Therefore, since forces occur in different directions during tripping in and tripping out, the hypothesis here is that the tubing is suffering buckling during its tripping in due to compression, while the tubing is not buckled during tripping out due to tension. The fact that the column buckles in only one scenario could explain the difference on the friction forces. This makes buckling as one of the two hypotheses for explaining the observed problem. The second hypothesis is that the problem is related to the dynamics of the system instead of its static response. Commercial simulators are already able to describe the static behavior of such systems but they were unable to explain the problem, thus leading the authors to believe that the cause is dynamical.

On the literature, the topic of column vibrations has been extensively studied (Bailey and Finnie, 1960; Chin, 2014; Chung and Whitney, 1981; Finnie and Bailey, 1960; Han and Benaroya, 2002; Park et al., 2002; Sparks et al., 1982; Sparks, 2002). However, when talking about buckling, the works focused mainly on the static approach of the problem instead of the dynamic one; classic works regarding static buckling include Dawson and Paslay (1984), Lubinski et al. (1962) and Paslay and Bogy (1964), with Dawson and Paslay (1984) still being widely used on commercial software. More recently, Gao and Miska (2009) studied the static configuration of a column after buckling while considering the effect of friction. Despite all the focus on the static problem, little attention was given to the dynamic approach. The work done by Gao and Miska (2010) is the most relevant regarding dynamic buckling, but their model does not consider friction. Therefore, the aim of the present work is to further develop the dynamic model by considering friction through usage of the ideas already present on the literature, especially from Gao and Miska (2009) and Gao and Miska (2010). Finally, the model will be expanded for directional and offshore wells, since the model from Gao and Miska (2010) is valid only for a purely horizontal segment and for an onshore well.

The results obtained show that, in fact, the friction force is different during tripping in and tripping out a column inside a well. Then, more complex models to consider the well trajectory as well as the heave motion of a column fixed on a floating vessel were developed, and the friction force still remained different in these two cases. Also, it was possible to see the effects of the well inclination and the heave motion on the dynamic behavior of columns.

2. Theoretical foundation

In order to fulfill the proposed objectives, mathematical models will be described on this section. The procedure used to create the model was incremental: four models were developed, with each model pushing the previous one a step further. The problem starts with Model I, which is exactly the same as proposed by Gao and Miska (2010). This is considered the base model, since it the most simplified one. On this model, there is no friction, the well segment is always horizontal and the boundary at x=0 is fixed. Improving this model there is Model II, which considers the friction force – but the segment is still horizontal and the boundary at x=0 is still fixed. It is worth noting that Model II is the minimum requirement to prove the hypothesis that the friction force is different during tripping in and tripping out. Moving further, Model III considers the well inclination as well; therefore, any well trajectory can be studied, as long as the angle at each depth is provided. Finally, Model IV considers a periodic excitation at the boundary x=0. This is a necessary improvement to consider a sea environment, since the column is subjected to a heave motion caused by the vessel heave motion; Models I to III can be applied only to onshore wells, where the wellhead does not suffer any kind of periodic motion. Also, while all models are subdivided into a tripping in case and a tripping out case, the column is not actually moving forward or backward; all models consider a fixed length of column vibrating freely around its equilibrium position for that very specific length, but under different hypotheses depending if the column is on a tripping in case or on a tripping out case. This also means that since the column is on a free vibration around its equilibrium position, no actual external force was considered either pushing or pulling the column from the well. Finally, this work is not focused on determining the critical buckling load in any section of the wellbore. This has been done for curved sections of wellbore in He and Kyllingstad (1995). Instead, a dynamic analysis is proposed assuming that buckling can either occur – model for tripping in – or does not occur at all – model for tripping out. This assumption is in accordance with previous works in literature (Mitchell, 1988, 2002; Gao and Miska, 2009, 2010). More details on the models presented below – such as the full deduction of