Parametric study of a tubing string buckling model with friction in petroleum wells

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Abstract. This work presents a parametric study of a buckling model with friction applied to tubing strings while production or injection of fluids occurs in a petroleum well. The tubing buckling can lead to structure failure, and to new regions of contact between the string and the casing. In these regions, frictional forces seem to have an important impact on the tubing elongation. In addition, ignoring friction might not be a conservative design strategy. To achieve the proposed objective, the adopted methodology is divided into three main stages: i) study of buckling models with friction for tubing strings; ii) implementation and validation of the chosen model; iii) definition of the scenario and variables for the parametric study, such as tubing and casing diameters and well depths. The main contribution of this work is quantifying how friction's relevance on buckling varies with tubing and casing diameters.

Keywords: Tubing string, Buckling, Friction

1 Introduction

In completion projects, buckling analysis of the tubing string is necessary, mainly because of the ever deeper oil reservoirs exploration. According to Bellarby [1], the occurrence of this phenomenon in tubing can result in large tubing-to-casing contact forces. In the presence of friction, they can restrict the axial loading along the tubing. Furthermore, there is a torque on connections that, under extreme cases, can even unscrew them, as well as doglegs that can limit access to the tubing.

As illustrated in Figure 1, there are two types of buckling in tubular: sinusoidal and helical. Pattillo [2] explains that initially, sinusoidal buckling occurs, and as the compression increases, there is abruptly helical buckling. However, this does not occur in vertical wells, so the transition is immediate and the tubular appears to buckle only helically. To characterize this stability, the concepts of effective and critical force are common. The effective force that consider the effect of fluids and pressures on the tubular. And the critical force that consider the beginning of each mode.

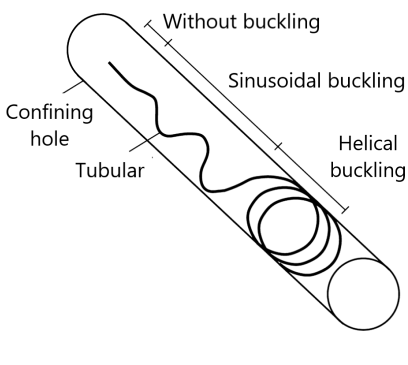

Figure 1. Buckling in tubular. Source: Modified from Pattillo [2].

As mentioned before, the buckling of tubing string generates contact forces (friction) between tubing and casing. According to Mitchell [3], this is perhaps the most important force, but the least studied in buckling. Hammerlindl [4], for example, assigns the measured length difference and that obtained by its equations to the friction between the tubing and the casing. Below are some works that address buckling and/or friction in the tubular under study.

Lubinski et al. [5] proposed a frictionless helical buckling model for tubing sealed in packers with free and limited motion. Mitchell [6] incorporates friction into the Lubinski et al. [5] model and develops an analytical friction buckling solution for two cases: tubing loaded at the packer and tubing slacked off at the surface. Mitchell [7] generalizes the analytical solution to [6] and presents a numerical formulation that considers the effects of friction on axial forces and tubing displacements. Zwarich et al. [8] developed a dynamic model for the design of tubing and casing with friction.

In this context, the objective of this work is to carry out a parametric study of a friction buckling model for petroleum wells tubing string. The main contribution is to identify the influence of the tubing and casing diameter, according to the model and the studied scenario.

2 Methodology

The methodology consists of three steps to achieve the proposed goal. The first step corresponds to the study of friction buckling models. Thus, studies of concepts related to buckling and friction in tubing strings and a bibliographic revision of friction buckling models are carried out. The criterion for choosing the model in the parametric study was application in vertical tubing and static analysis.

The second step involves the implementation and validation of the chosen model. To do so, the interpreted programming language Python™ [9] is used. Some scenario of the model described in the literature is reproduced to confirm the implementation. The agreement of the tubing force and length change fields with the results available by reference is evaluated.

The third step provides the definition of variables and a scenario for the parametric study. The geometric variables are selected because the friction in the model is described only by a coefficient, that is, the tubing and casing diameters. As for the study scenario, it is the same used in the validation of the implementation.

3 Buckling model with friction for tubing string

The friction buckling model for tubing string adopted in this work is proposed by Mitchell [6]. The formulation developed for the tubing loaded at the packer is used. Therefore, a fictitious or buckling force, $F_f(z)$, is admitted, (eq. 1):

$$F_f(z) = \sqrt{\frac{W}{K}} \tan[\sqrt{WK}(z-n)], \tag{1}$$

where z is the axial coordinate, n, W and K are, respectively, the neutral point, the buckling load distributed per length and a parameter associated to the annular cross section geometry, given by Eq. 2, 3 and 4

$$n = L - \arctan\left[\sqrt{\frac{K}{W}} F_f(L)\right] / \sqrt{WK}, \tag{2}$$

$$W = W_t + W_i - W_o, \tag{3}$$

$$K = \frac{rf}{EI}, \tag{4}$$

where L is the length of tube, $F_f(L)$ is the boundary condition of the buckling force applied to the packer, W_t, W_i and W_o are the weights per length of tubing, fluid in tubing and outside fluid displaced by tubing, respectively. r is the radial clearance between tubing and casing, f is the friction coefficient, E and I are the tubing's Young modulus and moment of inertia, respectively. In opposition to the fictitious force, which serves to measure the buckling, there is the actual force, $F_a(z)$, given by Eq. 5

$$F_a(z) = F_f(z) + (W_t - W)z + c_a, \tag{5}$$

where c_a contains the boundary condition for the actual force at the base of the tubing. The length change caused by buckling, ΔL_2, for the neutral point within the tubing ($0 \leq n \leq L$) is given by Eq. 6

$$\Delta L_2 = \frac{-r}{2f} \ln \left[1 + \frac{K}{W} F_f(L)^2 \right]. \tag{6}$$

To get the model equations without friction, is necessary to calculate their limits with f tending to zero. In this work is adopted that compression is positive (> 0) while traction is negative (< 0).

4 Results

The results of the model validation and parametric analysis are presented in this section. The scenario presented, for example, in Mitchell [6] is used, which refers to the squeeze-cementing operation. The tubing and annular are filled of crude oil with 30º API, while the tubing is sealed in a packer with free motion. Tubing fluid is displaced by a 15 lb/gal cement slurry and pressures of 5000 and 1000 psi are applied to the tubing and annular surfaces. According to [5] and [6], the characteristics of the tubing, casing, packer, and fluids are:

- Tubing: 2.875 in outside diameter, 6.5 lbf/ft weight, 10000 ft length and 30 x 10^6 psi Young's modulus;
- Casing: 7 in outside diameter, 32 lbf/ft weight and 10000 ft length;
- Packer: 3.25 in bore and at 10000 ft depth;
- Initial density of fluids: 0.0317 psi/in and 0.0317 psi/in at annulus and tubing, respectively;
- Final density of fluids: 0.0317 psi/in and 0.0649 psi/in at annulus and tubing, respectively.

4.1 Validation of model implementation

In Figures 2(a) and 2(b), the force and length change of the tubing by buckling for different friction coefficients are presented. In both cases, there is an agreement between the results obtained and the results presented by [6]. When considering friction, there is a reduction of the neutral point ($F_f(z) = 0$), that is, of the interval/length of the tubing under buckling. Tubing with a coefficient of friction equal to 0.4, for example, buckles from 10000 ft (base) to approximately 7500 ft. Furthermore, differences in tubing shortening due to buckling can reach more than 50% of depending on the coefficient.

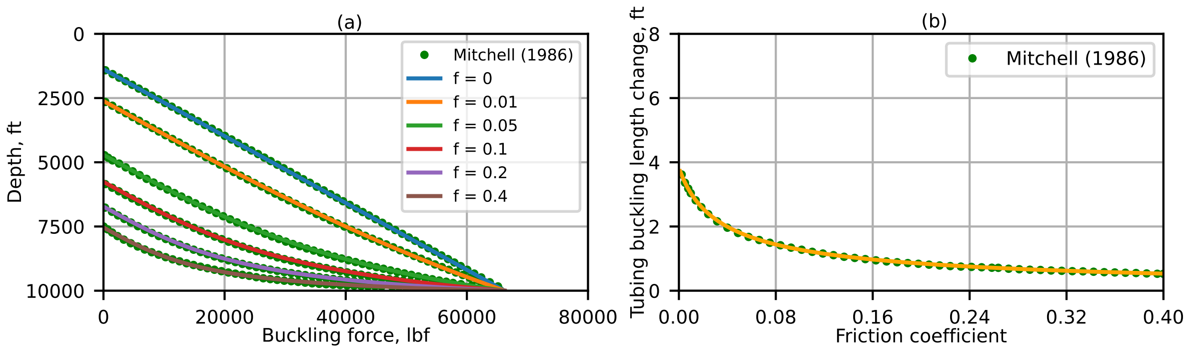

Figure 2. Buckling force distribution and tubing length change (shortening).

4.2 Analysis of the influence of tubing diameter

In this analysis, the previous scenario and tubing strings with the properties illustrated in Table 1 are considered. The friction coefficient is 0.2, as it is an intermediate value between those presented above.

Table 1. Diameter and weight of tubing strings.

Property	Tubing 1	Tubing 2	Tubing 3	Tubing 4
Outside diameter (in)	2.875	3.5	4.5	5.5
Weight (lbf/ft)	6.5	9.2	12.6	17.0

In Figure 3(a), the buckling force for the analysed tubing strings is illustrated. For tubing strings 1 and 2, it is observed a non-linear behaviour, for these cases the friction is significant, resulting in a decrease in length change with the diameter reduction. On the other hand, a linear behaviour is observed in tubing strings 3 and 4, for these cases the frictions is not significant, due to the inertia of the tubing, increasing the length change with the diameter reduction.

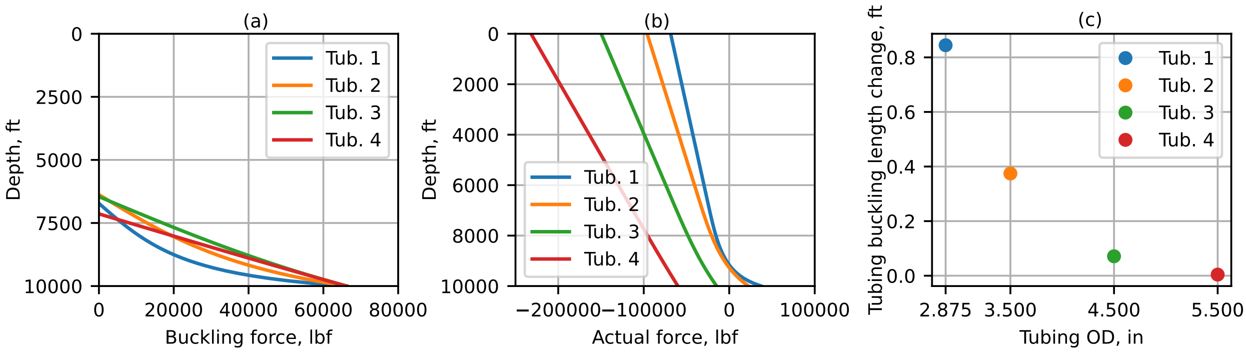

Figure 3. Forces and length variation (shortening) of tubing strings with different diameters.

In Figure 3(b), the actual force on the tubing strings is illustrated. As the diameter increases, tensile efforts predominate, for example, in tubing strings 3 and 4. However, according to the presented buckling force, the tubing still buckles. Cases like this occur due to fluid pressure inside the tubing [1]. In Figure 3(c), the shortening of the tubing strings by buckling is shown. As expected, these length variations are more pronounced for smaller diameter strings. The difference in tubing shortenings with 2.875 in and 3.5 in, for example, is 55.65%. Note that, for non-linear buckling force behaviour (2.875 in and 3.5 in), grater range of buckling is not associated to greater length change.

4.3 Analysis of the influence of casing diameter

In this analysis, the parameters are the same as the validation scenario, but casing are according to the properties illustrated in Table 2. The friction coefficient is also 0.2.

Table 2. Diameter and weight of casings.

Property	Casing 1	Casing 2	Casing 3	Casing 4
Outside diameter (in)	6.625	7.0	9.625	10.75
Weight (lbf/ft)	28.0	32.0	47.0	60.70

In Figure 4(a), the buckling force for the tubing strings is illustrated, according to the casing diameter. As the annular grows, the length of the tubing under buckling decreases. Furthermore, due to casings with close diameters (casings 1, 2 and 3, 4), the variation of the buckling force is not expressive. Neutral points for tubing strings with casings 1 and 2, for example, are 6594.19 and 6723 ft, respectively.

In Figure 4(b), the actual force on the tubing strings is illustrated. As the casing diameter increases, the tensile stresses also increase towards the same point in the tubing. Despite this, compression efforts remain. This is because the actual force at the base (10000 ft) is a boundary condition that does not depend on the casing or annular characteristics. In Figure 4(c), the shortening of the tubing strings by buckling is shown, according to the casings. As expected, the increase in casing diameter implies more space available for tubing buckling. The difference in tubing shortenings with casings of 6.25 in and 10.75 in, for example, is 67.60%. In this case, the fact that the neutral point is higher (longer buckling length), does not imply an increase in the shortening of the tubing, but in fact it is the opposite.

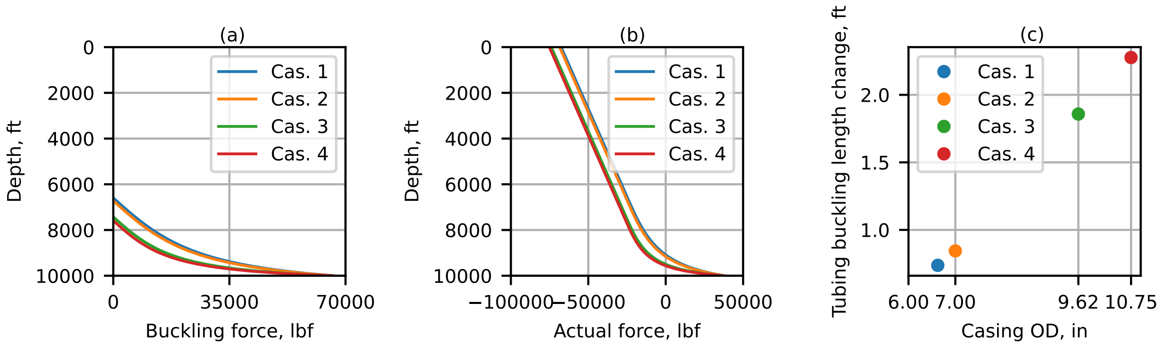

Figure 4. Forces and length variation (shortening) of tubing strings with different casings.

5 Conclusions

A parametric study of a friction buckling model for tubing string was carried out, using tubing and casing diameters as variables. The model adopted was duly implemented and validated. In the parametric analysis of the tubing diameter, a limit diameter is suggested to define the influence of friction on buckling. For cases where friction is significant, a longer buckling interval does not necessarily imply greater buckling shortenings. In the parametric analysis of the casing diameter, the annular growth means the decrease in the length/interval of the tubing under buckling. Furthermore, increasing the casing diameter elevates the buckling shortening. Properly understanding and quantifying buckling loads and their length changes is essential to design a safe and economically efficient well, this work provides interesting information to assist in the selection of tubing and casing diameters.

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