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Research Article

Design and Analysis of Drilling String Buckling in Directional Wells

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Abstract

This study investigated tubing buckling in vertical and deviated wellbores outlining the various existing correlations with more emphasis on the deviated wellbore. In this study, a computer model was developed using Microsoft visual basic.net programming language for the determination of the critical buckling load limit from existing measured data. Theoretical data gotten from an application problem in Mitchell's "buckling analysis in deviated wells" was used for the analysis and validation of the PIBUCK analyzer. Some models were used to analyze tubing buckling and the critical buckling force with its post buckling configuration obtained. The study showed that the critical buckling loads increased as the well inclination increased. The output results from PIBUCK software was compared to the results of Mitchell's analysis and the results showed good accuracy with an average error of 0.11% for the critical buckling load estimation. For the post buckling configuration analysis, PIBUCK results showed good accuracy when compared to results from Mitchell's analysis with an average error of just 2.25% in estimating bending stress and an average error of just 4.32% in estimating the tubing length change. The PIBUCK software developed proved to be reliable, simple to use and accurate.

Keywords: *The Pipe buckling; deviated well; Lateral buckling; Helical buckling; Bending stress.*

1. Introduction

Petroleum engineering is a field that has constantly evolved during these past decades. As a result, more oil wells are been discovered with designs and techniques being developed to meet its present challenges. There is a need for these oil wells to be drilled more efficiently so that cost could be minimized and profit maximized. Wells could be vertical, horizontal or deviated. However, the subject area of interest for this research study is tubing buckling in deviated wells.

Deviated wellbore are wellbores drilled and deflected from the vertical at an angle of inclination in order to access a particular formation and meet desired target using directional drilling techniques. The directional drilling techniques used however doesn't come without challenges while drilling a deviated well. Some of these challenges to mention a few would include; drill string rotation which induces cyclic stress initiating pipe failure, rate of penetration, pipe buckling and casing damage due to applied load on the drilling bit after compression amongst others.

Pipe buckling been considered is defined as a form of instability which causes the pipe or tubing to lose some of its strength and mechanical properties as a result of too much weight or torque on the drilling bit. Tubular buckling is a challenge that could occur when drilling activities takes place, thereby making it difficult to carry out well completion and workover operations.

Most drilling activities are capital intensive; hence there is a need to take into consideration any buckling tendencies that may occur as a result of the operations during the design stage. Buckling can be caused by moments while the tension created is caused by stress. In most drilling literature, the buckling tendency is usually given as the sum of all the moments acting in a particular location within the tubing. It can also be referred to as the effective tension or fictitious force. Some factors which may create buckles in oil tubular include: Temperature; Surface pressures; Fluid densities; Slack off and Evacuations. Other factors that could affect buckling include the angle of inclination and radial clearance between the borehole and pipe.

This subject area is one critical research area that has been the focal point of interest for previous researches in the past five (5) decades. Lubinski et al., (1950) were the first to work on pipe buckling behavior in oil wellbores. They derived the first set of equations for a perfect vertical wellbores without friction. They based their model on certain assumptions using virtual work relation to predict the well load as a function of the buckling configuration. However, one of their limitations was the validity of the solution developed for deviated wellbores due to the presence of lateral gravity forces. Drill pipe buckling behaviour in an inclined wellbore was initially

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suggested by Dawson and Paslay (1984) based on existing studies by Paslay and Bogy (1964) which is very useful in the oil industry. They worked on the strength and snake-like buckling of a pipe restrained in an inclined wellbore using energy method and they derived a formula for calculating axial force. Mitchell (1996, and 1997) extended the Lubinski helical buckling model by solving the buckling problem using approximated analytical and numerical methods. He developed a full deviated well equation and put his result in a more usable form.

His work however, would form vital basis for this study. Mitchell (1999) noted that the fluid pressures influence both the axial buckling thrust and the tubing lateral weight. Mitchell (2005) further stated that the internal and external pressure of pipes both have a significant impact on the drill string. Therefore, an increase in the internal pipe pressure comes with an increase in the volume which the tubular can contain. Its containment volume can therefore be increased by either an increase in its diameter or length. The study of the buckling behaviour by the use of both the tubular buckling equations and the virtual work principle were carried out by Gao (2006), Gao and Miska (2009, 2012) and Liu (1999). The results obtained by these researchers are being widely used in various engineering practice. Considering the buckling behaviour study carried out by Liu (1999), Gao and Miska (2009), a classic tubular buckling equation was obtained neglecting the shear force and the bending moment at the string end while using the virtual work principle. Also, Mitchell (1988) and Gao (2006) developed a 3D BHA model from the general bending and twisting theories of rods. Chen et al. (1990) found the buckling criteria for a pipe that is helically buckled in deviated wellbores. Dosunmu et al., (2012) presented a new development from their studies on tubular buckling simulation which is incorporated in a recent advance model for drill string mechanics. With this model therefore, one can safely determine the buckling load above which the tubular will buckle. Duman et al. (2003) carried out experimental works to show the essence of tool joints on the contact and axial force transfer in horizontal wells. The result of the connector however on the critical buckling load and post-buckling behaviour has not been considerably studied or interpreted. Menand et al. (2006) showed that rotation and tortuosity has strong consequences both on the axial force transfer and the critical buckling loads.

They have shown, for instance that the critical helical buckling load of a rotating pipe is about 50% to that gotten for a non-rotating. Huang et al (2015) in considering the effect of boundary conditions emphasized that previous works neglected the outcome of the lateral force and the bending moment on the boundary restraints but mainly considered only the axial force effect in their studies. Huang et al. however suggested a new categorization method for the boundary considerations. Wu and Juvkam-wold (1993b, 1995) noted that the transition section can be ignored if the buckled pipe has about 3.5 or more pitches of the helix.

Mathematical models for determining the critical pipe buckling loads both in vertical and deviated oil wells have been developed. The scaling factor has over the years been a distinguishing factor for these developed mathematical models. The question now remains how many of these models have been translated into computer based codes to give the driller or engineer real time monitoring and on site knowledge about buckling and its tendencies. The world is a global village in which modern technology are being developed to meet its present challenges. How accessible and easy to use are the graphic user interface (GUI) of these software developed? Therefore, the essence of this research work is not just to write a computer based code for each of these models but to assemble different available model to predict buckling in pipes and their post buckling configuration with the aim of comparing and making necessary deductions thereby adding to the pool of knowledge. In order words, it involves developing a platform where all the mathematical models have been translated into codes giving any user easy interface to select on any he or she wishes to use to predict and analyzing tubing buckling using available data. Some of the software are usually complex, cannot be run on all windows operating system and might be difficult to use. Hence, there is a need for cheaper and easy to use software for pipe buckling analysis in the petroleum industry. This research study was therefore aimed at providing simplicity in analyzing tubing buckling in deviated wellbores by using an integrated software development platform with an easy to use graphical user interface.

2. Methodology

This research study made use of Microsoft visual basic, an integrated software development platform from Microsoft with an easy to use graphical user interface (GUI) as its development tool. PIBUCK (2107) was developed to provide simplicity in analyzing pipe buckling in a deviated wellbore. The programming language is very important and necessary because this will assist in giving the end user a simplified variety of ways to analyze pipe buckling using different imputed correlations. The design strategy adopted for this program design is modular and top-bottom approach. The software is divided into modules; thus the main module is the module that coordinates all other modules in the program. It is also the driving engine of the application. The other modules were named according to the author of the various models used. In addition, the software has a window interface that contains the main menu. However, the different menus activate the different sections when the need arises.

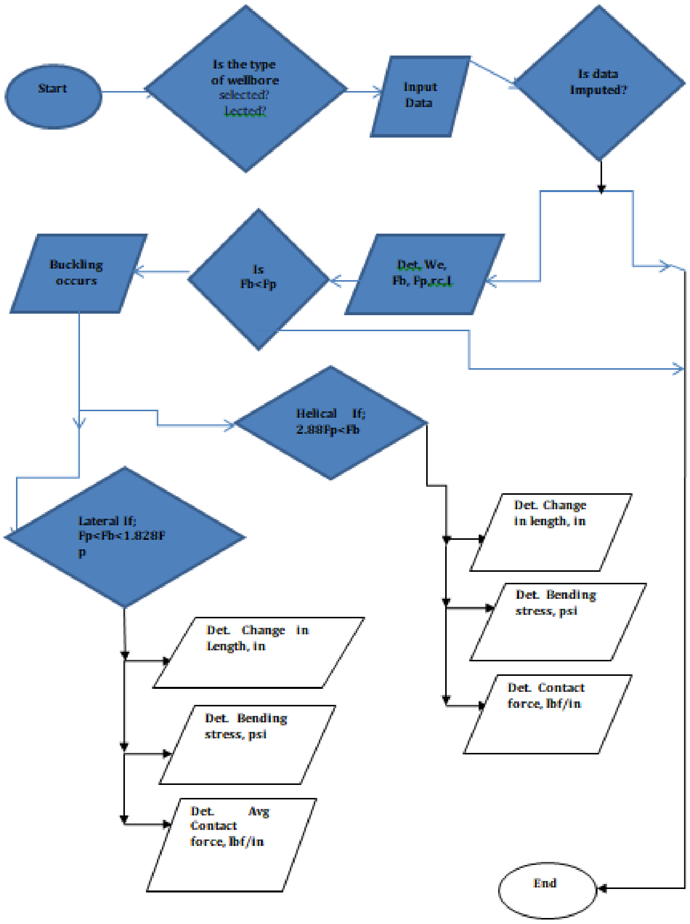

Fig. 1 Flow chart for the buckling analysis

2.1 Input well data parameters for software analysis

The well input parameter data for this research study comprises of the tubing-casing properties which include the type of tubing with its external and internal pipe diameter, tubing weight, fluid location and type amongst others as shown below in the appendix. A constant hole diameter and a varying well deviation was used for this study. The pipe buckling analyzer carries the input value for the various basic well parameters used in the research study such as angles of inclination, the input values when calculating the buoyed weight of the pipe per unit length with a known pipe diameter or using the buoyancy factor.

The flow chart for this software development is shown in Figure 1 above. This provides a path for calculation and analysis of tubing buckling in deviated wells. For deviated wells, the software determines the fictitious force also known as the buckling force F_b and also the minimum critical buckling load required to initiate sinusoidal or lateral buckling which is known also the Paslay forceF_p. The software performs analysis using a set buckling criterion in calculating the critical buckling load for the various types of buckling as captured in the flow chart. They include the lateral phase, the transition phase (lateral or helical) and the helical phase. With these buckling criteria in place, the maximum bending stress, minimum lateral buckling force, maximum lateral buckling force, minimum helical buckling force and buckling length change due to either lateral or helical buckling were estimated and the output result displayed for easy reference

2.2 Software testing and validation

The verification of the developed pipe buckling analyser was done using literature data obtained from a theoretical case study well to determine if the computer based model implementation and its data accurately represent the set objectives and specifications. The validation of the developed software program was done using the same data and the output results compared with results of Mitchell's publication titled "Buckling analysis in deviated wells".

2.3 Mathematical equations used to develop PIBUCK

The critical buckling force is also called the buckling force. Buckling would normally occur when the threshold force (F_p)is less than the buckling thrust (F_b). For this research study, the calculation for the buckling force is given below by equation (1)

$$F_b = -F_a + P_i A_i - P_o A_o \qquad (1)$$

Where;
P_i = fluid internal pressure within the pipe, psi

Fa = Axial Force, lbf
P_o = The external fluid pressure, psi
A_i = pipe internal flow area, in^2
A_o = The pipe external flow area, in^2

The buoyed weight of the tubing per unit length in a wellbore which was calculated as follows:

$$W_i = MW_i \times \frac{A_i}{231} \quad (2)$$

$$W_o = MW_o \times \frac{A_o}{231} \quad (3)$$

W_s = The weight of the steel or pipe per unit length, lbf/ft

$$W_e = W_s + W_i - W_o \quad (4)$$

Where;
W_e = buoyed pipe weight of per unit length, lbf/in
Alternatively, the buoyed tubing weight can be also calculated as follows:

$$W_e = W_s + 0.0408[MW_i \times D_i^2 - MW_0 \times D_o^2] \quad (5)$$

Where;
MW_i = initial mud weight inside the tubing, lbm/gal
MW_o = final mud weight outside the tubing, lbm/gal
W_i = The fluid weight inside the pipe per unit length, lbf/in
W_o = The fluid weight outside the pipe per unit length, lbf/in

The axial moment of inertia for this research study was calculated as shown in equation (6) below. This is however given as:

$$I = \frac{\pi}{64}[D_o^4 - D_i^4] \quad (6)$$

Where;
I = the axial pipe moment of inertia, in^4
Consequently, the polar moment of inertia can also be obtained by equation (7) below.

$$J = 2I \quad (7)$$

Where;
J = polar moment of inertia, in^4
It should also be noted that the young modulus of steel, E used for this research study was given as 30×10^6psi.
In addition, the radial distance between the wellbore wall and the constraining pipe, (in) was calculated as follows using equation (8) below.

$$r_c = \frac{1}{2}[OD_{HOLE} - OD_{TUBING}] \quad (8)$$

Where;
r_c = The radial distance between the wellbore wall and the constraining pipe, in
OD and OD Are both outer diameter for the hole and tubing,

The lateral buckling calculation in this research study was done using Dawson and Paslay (1984) minimum force criteria required to initiate buckling.

$$F_p = 2\sqrt{\frac{EIW_e sin\theta}{r_c}} \quad (9)$$

Where;
F_p = Paslay buckling force, lbf, E = Young's modulus
The helical buckling calculation was done using Wu et al. (1990) and Mitchell (1997) correlation.

$$F_{chel} = 3.66\sqrt{\frac{EIW_e sin\theta}{r_c}} \quad (10)$$

$$F_{chel} = 5.66\sqrt{\frac{EIW_e sin\theta}{r_c}} \quad (11)$$

Equation (10) is the minimum helical buckling force while equation (11) is the maximum lateral buckling force used in this research study.

The bending moment calculation in this research study was done as follows using the following equation.

The bending stress for this research study was calculated using the following equation for the different mode of buckling shown below.

$$\sigma_b = 0 \quad ; \text{For } F_b < F_p \text{ [no buckling]} \quad (15)$$

$$\sigma_b = \frac{0.3151 D_o r_c}{I} F_b^{0.08}[F_b - F_p]^{0.92} \quad (16)$$

For $F_p < F_b < \sqrt{2}F_p$

$$\sigma_b = \frac{0.25 D_o r_c}{I} F_b \quad (17)$$

For $2\sqrt{2}F_p < F_b$

Where;
σ_b = Bending stress, psi

The change in length caused by buckling for the two (2) buckling mode occurring in a deviated wellbore was calculated using the equation (18) and (19) shown below below.

$$\Delta L_b = -\frac{r_c^2}{4EIW_e \cos\theta}[F_{b2} - F_p][0.3771F_{b2} - 0.3668F_p] \quad (18)$$

For $F_p < F_b < \sqrt{2}F_p$

$$\Delta L_b = -\frac{r_c^2}{8EIW_e \cos\theta}[F_{b2}^2 - F_{b1}^2] \quad (19)$$

For $2\sqrt{2}F_p < F_b$

The calculation for the contact force for lateral buckling was done using Wu's equation given as:

$$W_n = W_e \sin\theta + \frac{r_c F_b^2}{8EI} \quad (20)$$

While that for helical buckling as used in this research was the Mitchell contact force equation given as:

$$W_n = W_e \sin\theta + \frac{r_c F_b^2}{4EI} \quad (21)$$

Where;
ΔL_b = Change in length due to buckling, in;
Wn = Contact force, lb/in

2.4 The Buckling Criteria

The buckling criteria as used in this present research study are shown below in Table 1. The available buckling force for each of the mode of buckling is also presented. These criteria show the buckling force magnitude and their corresponding result.

Table 1 PUBUCK Software Buckling Criteria

The Buckling Force Magnitude	Result
$F_b < F_{paslay}$	No Buckling
$F_{paslay} < F_b < 1.828F_{paslay}$	Lateral Buckling
$1.828F_{paslay} < F_b < 2.828F_{paslay}$	Transition between Lateral or Helical Buckling
$2.828F_{paslay} < F_b$	Helical buckling

The following assumptions were employed in developing the pipe buckling analyzer and also in the analysis of buckling for the deviated wellbore. They include:

The tubing curvatures are ignored and the angle of inclination has a significant effect on buckling; the angle of deviation is the only parameter that is assumed to vary in the analysis for the critical buckling load with a fixed hole diameter; the use of packers and centralizers are ignored and the radial clearance considered having significant effect on the critical buckling loads; the wellbore is assumed to be deviated and the friction effect ignored and lastly the tubing is presumed to buckle into a lateral and helical shape.

3. Results and discussion

The theoretical case study used in this study was based on the results of Mitchell's study in his publication titled "Buckling analysis in deviated wells". The tubing, casing and fluid properties together with other parameters are summarized in the appendix. Two stages of configuration changes considered in this research study was the helical and lateral buckling onset. The critical buckling load was calculated for the various deviated angles as shown in Table 2 below. The significance of well deviation and its importance on the buckling results obtained is one cardinal focus in developing the pipe buckling analyzer.

Table 2 Results for critical buckling loads using PIBUCK predictor

PIBUCK Analyser			
Deviation angle (deg °)	Minimum lateral buckling (lbf)	Maximum Lateral buckling (lbf)	Minimum Helical buckling (lbf)
10	3656	10340	6684
20	5131	14512	9381
30	6203	17546	11343
40	7034	19894	12861
50	7678	21718	14040
60	8164	23092	14928
70	8504	24054	15550

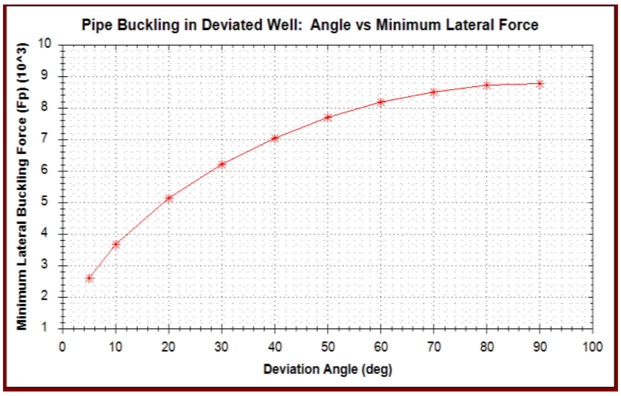

Fig. 2 Plot to show the minimum lateral buckling forces plot using PIBUCK Predictor

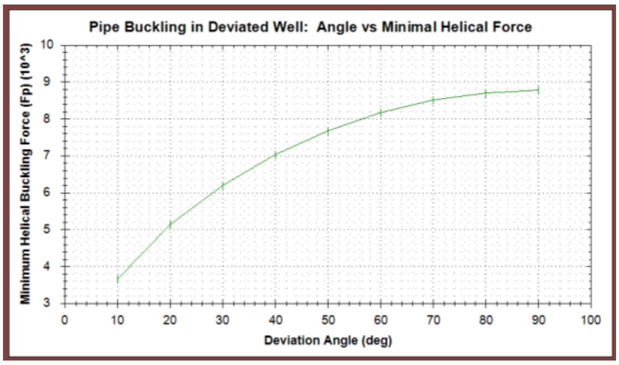

Fig. 3 Plot to show the minimum helical buckling forces plot using PIBUCK Predictor

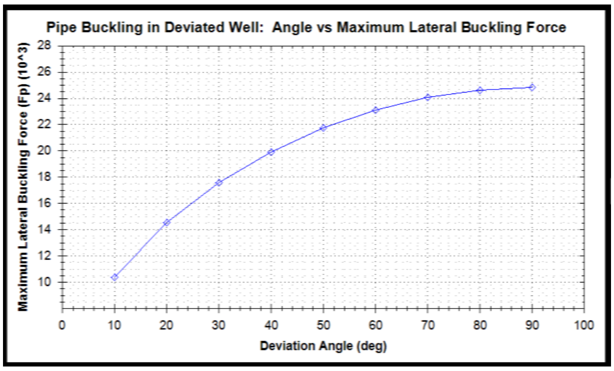

Fig. 4 Plot to show the maximum lateral buckling forces using PIBUCK Predictor

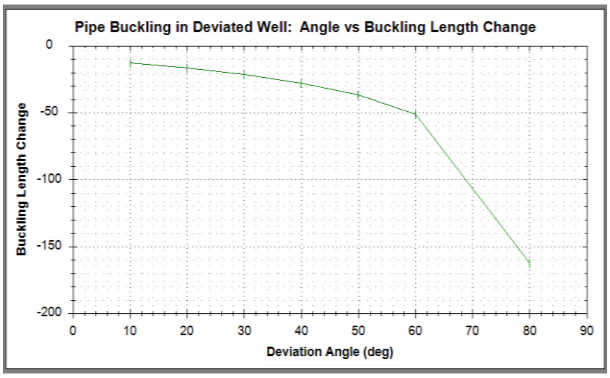

Fig. 5 Plot to show buckling length change using PIBUCK analyzer

Table 3 Results of normal contact force using the pipe buckling analyzer

		Normal contact force, W_n	
Deviation angle, (deg °)	Buckling force, (lbf)	Lateral buckling, (lbf/in)	Helical buckling, (lbf/in)
10	35,101	5.24	10.38
20	39,162	6.6	12.98
30	42,655	7.9	15.48
40	45,685	9.1	17.79
50	48,223	10.17	19.85
60	50,235	11.06	21.57
80	52,611	12.15	23.68

Table 4 Comparing the critical buckling loads obtained for lateral buckling

			Lateral buckling load(lbf)		
Tubing		Deviation angle(°)	Pipe buck analyzer (lbf)	Mitchell's Result (lbf)	% Error
Based on the tubing diameter(in)	2.875	10	3656	3652	0.11
		20	5131	5125	0.12
		30	6203	6197	0.10
Tubing weight (lbf/ft)	6.5	40	7034	7026	0.11
		50	7678	7670	0.10
		60	8164	8155	0.11
		70	8504	8495	0.11

Table 5 Comparing the critical buckling loads obtained for helical buckling

			Helical buckling load(lbf)		
Tubing		Deviation angle(°)	Pipe buck analyzer (lbf)	Mitchell's Result (lbf)	% Error
Based on the tubing diameter(in)	2.875	10	10340	10329	0.11
		20	14512	14496	0.11
		30	17546	17528	0.10
		40	19894	19873	0.11
		50	21718	21694	0.11
Tubing weight (lbf/ft)	6.5	60	23092	23066	0.11
		70	24054	24027	0.11

Table 6 Comparing the applicable parameters for the post buckling configuration

			Pibuck Analyzer		Mitchell's result			
Tubing		Deviation angle	Bending stress (psi)	Buckling Length change (in)	Bending stress (psi)	Buckling Length change (in)	% Error (bending stress)	% Error (length change)
Based on the tubing diameter(in)	2.875	10	24,741	-12.46	23,965	-11.44	3.14	8.19
		20	23,846	-11.98	23,345	-11.32	2.10	5.51
		30	22,372	-11.26	21,980	-10.89	1.75	3.29
Tubing weight (lbf/in)	6.5	40	20,112	-10.13	19,678	-9.82	2.16	3.06
		50	17,873	-9.65	17,324	-9.56	3.07	0.93
		60	15,150	-8.66	14,895	-8.25	1.68	4.73
		70	12120	-8.23	11,897	-7.86	1.84	4.50

3.1 Discussion

For a fixed 6.094" hole section (Figure 2), the critical buckling force obtained by PIBUCK predictor shows an increase in the buckling forces as the deviation angles increases. Figures 2, 3 shows the effect of the deviation angle on the minimum lateral force, minimum helical force and the maximum lateral buckling force respectively. The bending stress is a function of the outer pipe diameter, the radial distance and the buckling force. It is important to state here also that a change from lateral to the helical buckling phase increases the bending stress.

The average contact force produced as a result of helical buckling tends to increase as the buckling force increases. From Table 3, it could be deduced that as the buckling manner transit from lateral to helical, the normal contact force which is a function of the force acting against the wellbore also increases. This value was however calculated by PIBUCK predictor for different well inclinations. When the buckling force decreases, the contact force would tend to decrease also.

The buckling length change tend to show the tubing movement behavior as the buckling force either increases or decreases with the corresponding angle of inclination. The results obtained by the pipe buckling analyzer, shows that the buckling length tends to decrease as the buckling force decreases. The tubing movement caused by helical buckling tends to produce a length change that shows a reduction as the well inclination increases. The tubing movement due to lateral buckling at a buckling load of 17,545 lbfproduces a much lower length change.

3.2 Software testing and validation

The testing and validation for this research studies was done by comparing the PIBUCK results against the results of Mitchell in his publication titled "Buckling analysis in deviated wells. The dawson and paslay buckling criteria was used to predict the onset of lateral buckling in a deviated wellbore. The results obtained are shown in Tables 4, 5 and 6.

Mitchell's result using the paslay buckling criteria for the onset lateral buckling when compared to the PIBUCK analyzer tend to give a good approximate result with an average error of about 0.11% as shown in Table 4. This shows the accuracy of the pipe buckling analyzer in performing its calculations. The helical force output from Mitchell's result was compared based on its buckling criteria as against the one used by the pipe buck analyzer and the results tend to be accurate and consistent with an average error of about 0.11% as shown in Table 5.

For the applicable parameters for the post buckling configuration as obtained using the developed software and results compared to the Mitchell's results using the same buckling length and bending stress equation for helical buckling, the results shows an average error of 2.25% for the bending stress generated as a result of buckling while an average error of 4.32% for the buckling length change as a result of buckling (Table 6). The difference obtained in this result might be due to the calculation for the buckling force, the buckling criteria and the significant decimal places employed using both software. However, the overall experience using the developed software lies in its ability to produce fast and near accurate results from its inputted data. The developed software from this study however showed good accuracy when compared to the Mitchell's results and it also showed that the critical buckling force increases with increase in well inclination.

Conclusion

Mathematical models for analyzing pipe critical buckling load, the post buckling configuration generated due to bending, internal and external tubing pressures in deviated wells were studied. A computer model (PIBUCK) was developed from existing mathematical correlations for an effective analysis of pipe buckling.

The output results from PIBUCK software was compared to the results of Mitchell's analysis and the results showed good accuracy with an average error of 0.11% for the critical buckling load estimation. For the post buckling configuration analysis, PIBUCK results showed good accuracy when compared to results from Mitchell's analysis with an average error of just 2.25% in estimating bending stress and an average error of just 4.32% in estimating the tubing length change.

The overall experience in using PIBUCK proves that it is cheap, reliable, simple to use and accurate.

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Appendix

Table 1 Tubing input parameters used in the thesis

Tubing outside diameter (D_o) = 2.875in	Nominal tubing weight (W_s) = 0.542lbf/in
Tubing inside diameter (D_i) = 2.441in	Inside tubing mud weight (MW_i) = 15ppg
Coefficient of friction (μ) = 0.2	Outside tubing mud weight (MW_o) = 7.3ppg
Modulus of elasticity (E) = 30000000psi	Fixed vertical true depth (TVD) = 120000in
Casing internal diameter (H) = 6.094in	Deviation angles = varying degrees (°)
External tubing pressure (P_o) = 4796psi	Internal tubing pressure (P_i) = 12800psi

Table 2 Tubing output parameters using the PIBUCK analyzer

Buoyed weight of tubing (W_e) = 0.64lbf/in	Radial tubing clearance (r_c) = 1.61in
Outside tubing area (A_o) = 6.492in2	Ratio of tubing OD to the tubing ID (R) = 1.178in
Inside tubing area (A_i) = 4.680in2	weight of fluid inside the tubing (W_i) = 0.342lbf/in
Cross sectional tubing area (A_s) = 1.81in2	weight of fluid outside the tubing (W_o) = 0.522lbf/in
Axial moment of inertia of tubing (I)= 1.61in4	