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Basic Tubing Forces Model (TFM) Calculation

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October 2003

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Summary

The purpose of this document is to describe how Orpheus calculates tubing forces. These calculations are needed to determine the stresses in Coiled Tubing (CT) to ensure the safe working stresses are not being exceeded. They also are needed to predict the behavior of the CT in a highly deviated well, to determine if the planned job can be done, or to determine if the job being executed is proceeding as expected.

Orpheus is a tubing forces model (TFM) written specifically for Coiled Tubing (CT). The basic TFM calculation is performed by calculating the forces along the length of a CT string at a specific depth in a well, as the string is being either run into the hole (RIH) or being pulled out of the hole (POOH). This calculation is performed beginning at the downhole end of the CT string and calculating the forces on each segment of the string, progressing up the string to the surface.

Introduction

The basic TFM calculation is performed by summing the forces on each segment as discussed above. This is performed with the end of the CT string at a specified depth. The basic calculation is explained by using a simple example in which a CT segment is located in a straight, inclined section of a well without fluids or pressures, shown in Figure 1. As is discussed later, the length of the segment could vary from a few feet to the entire length of the well depending on variations in well geometry and CT geometry.

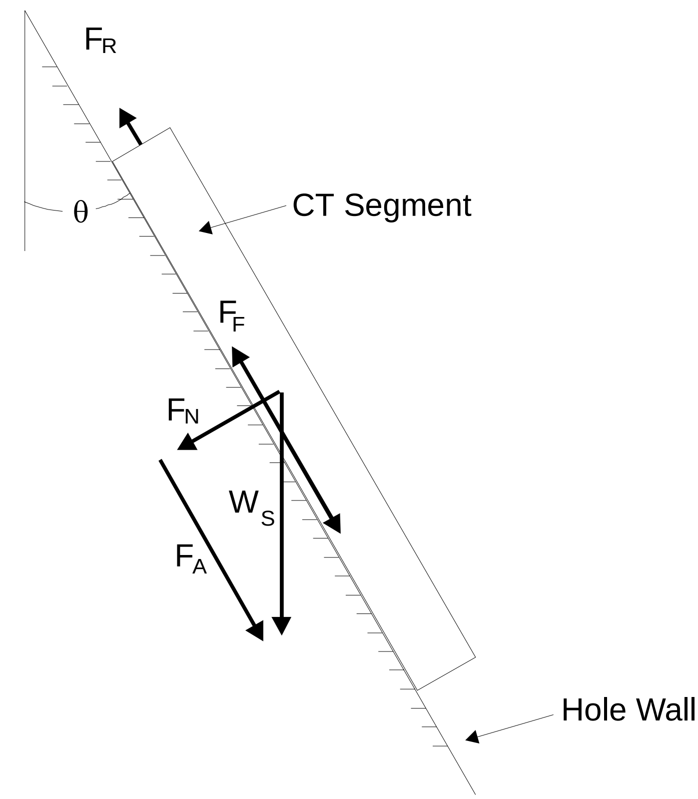


FIGURE 1 CT segment in a straight, inclined section of a well

The vector triangle in Figure 1 shows how a weight W_S can be broken into two component forces. F_A is the force component in the axial direction (along the axis of the hole). F_N is the force component in the normal direction (normal or perpendicular to the axis of the hole). The equations for each of these components are:

$$F_A = W_S \cos\theta \qquad \textbf{EQ 1}$$

$$F_N = W_S \sin\theta \qquad \textbf{EQ 2}$$

The friction force is calculated by multiplying the normal weight component by the friction coefficient μ.

$$F_F = \mu F_N \qquad \textbf{EQ 3}$$

The real axial force is found by summing the weight component in the axial direction, F_A, with the friction caused by the normal component of the weight, F_N. Note that the axial component of the weight causes F_R to be in tension, which is defined as a positive force. However, the sign of the friction force depends on the direction of motion. When RIH the friction causes a compressive (negative) force to be added to F_R. When POOH the friction causes a tensile (positive) forces to be added to F_R.

$$F_R = F_A \pm F_F \qquad \textbf{EQ 4}$$

This is the basic calculation for one segment of the CT. Summing the results from a series of segments up a CT string yields the axial force on the CT in the well along it's length. This force versus length profile is calculated by Orpheus when the "run at depth" function is executed.

The calculation for tripping the CT string in and out of the hole simply repeats the "run at depth" TFM calculation above for many specified depths, stepping the CT string into and out of the well. The amount of data calculated during tripping is more than can be easily displayed. Thus, only the forces at surface, commonly known as the "Weight", are displayed when the "trip in and out" function is used in Orpheus. Each of these values is the result of a TFM calculation along the entire length of the string in the well.

The basic TFM can be adapted to account for rotation of CT in the hole during either tripping (to achieve greater reach) or drilling (as a by-product of down-hole motors). In order for a segment of CT to be rotated, the frictional resistance opposing the rotational motion, F_{RF}, must be offset. Torque is the moment quantity which measures the ability of a force to rotate an object or oppose its rotation; it is equal to the force multiplied by the moment arm. So, T_F, the torque associated with the opposing friction, would be the frictional force multiplied by the outer radius of the CT.

$$T_F = rF_{RF} \qquad \textbf{EQ 5}$$

The incremental torque associated with frictional contact between CT and casing surfaces must be calculated for each segment and summed up the length of the CT string in exactly the same manner as real axial force, F_R, is calculated.

Since the friction force acts in the direction opposite of motion, a simple analysis of the velocity vectors of the CT during tripping or drilling provides a direct way to distribute some or all of the normal wall contact force between F_F and F_{RF}. If the axial velocity of the CT is V_A and the equivalent linear velocity of rotation is V_R, then the resultant velocity V_{CT} is the vector sum of V_A and V_R, as shown in Figure 2.

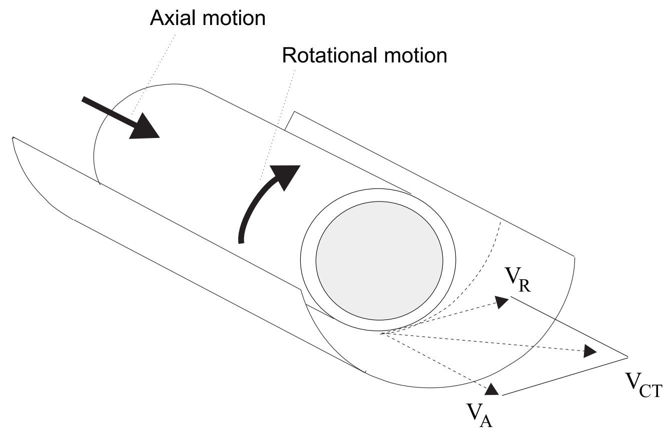


FIGURE 2 CT segment moving axially and rotationally

The actual friction force will be in the direction opposite of V_{CT}. Based on the velocity vector angle between V_{CT} and V_A, denoted by β, the axial and rotational components of friction resistance can be calculated.

$$F_{RF} = \mu F_N \sin\beta \qquad F_F = \mu F_N \cos\beta \qquad \textbf{EQ 6}$$

If the CT string is continuously rotated while tripping into and out of the hole, then any initial static friction may be ignored. In this case, the opposing torque due to friction is cumulative for all segments up to the top. However, in the case of conventional CT drilling, the CT string itself is initially static. In this case, any torque caused by the down-hole motor is “damped out” by the torque associated with the drag of each CT segment. Since this is essentially a statics problem, a worst case solution is attained by applying the entire friction force to both axial and rotational drag.

Theoretical Concepts

The above description of a basic TFM only took into consideration mass and friction, and ignored the more complex issues of internal and external pressure, helical buckling, etc. In this section the more difficult concepts are discussed.

Real versus Effective Force

There is often confusion about the difference between the real axial force (F_R) and the “effective force” (F_E), sometimes called the “fictitious force”. Suri Suryanarayana of Mobil has clarified this situation. This clarification is documented below using a simple example. Imagine a closed ended pipe suspended in a well as shown below:

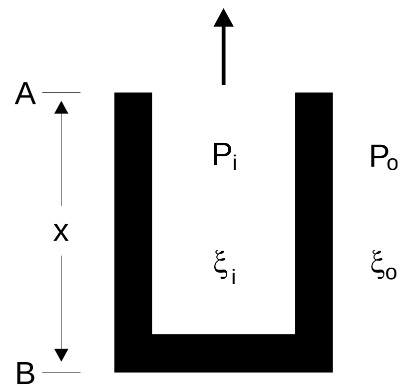


FIGURE 3 Closed ended pipe suspended in a well

Let us consider only the lower section of this pipe from some point “A” downward. The variables used in this discussion are defined in the nomenclature at the end of this document.

The axial force components acting below point A are:

1. weight of the pipe acting downward = $W_S X$
2. upward force on the end of the pipe due to the external pressure = $P_{oB} A_o$
3. downward force on the end of the pipe due to the internal pressure = $P_{iB} A_i$

Summing these forces to obtain the real axial force at A yields:

$$F_R = W_S X + P_{iB} A_i - P_{oB} A_o \quad \textbf{EQ 7}$$

P_{iB} and P_{oB} can be calculated as follows:

$$P_{iB} = P_{iA} + X\xi_i \qquad \textbf{Eq 8}$$

$$P_{oB} = P_{oA} + X\xi_o \qquad \textbf{Eq 9}$$

Defining the buoyant weight per foot as:

$$W_B = W_S + \xi_i A_i - \xi_o A_o \qquad \textbf{Eq 10}$$

Substituting Eq 8, Eq 9, and Eq 10 into Eq 7 and arranging terms yields:

$$F_R = W_B X + P_{iA} A_i - P_{oA} A_o \qquad \textbf{Eq 11}$$

Another force, the “effective force” is now defined as:

$$F_E = F_R - P_{iA} A_i + P_{oA} A_o \qquad \textbf{Eq 12}$$

Note that this is a definition, not a real physical force. The effective force is the real force without the effects of pressure included. This force turns out to be much more convenient to work with for several reasons. Note that the effective force at point A can now be written by combining Eq 11 and Eq 12 as:

$$F_E = W_B X \qquad \textbf{Eq 13}$$

This is a much simpler equation to work with in a tubing forces model than Eq 11. Also, as shown in the Tech Note “The Effective Force”, the buckling characteristics of a pipe depend upon the effective force, not the real force. The physical significance is that buoyancy, which is independent of depth, affects buckling; however, pressure, which is dependent on depth, does not affect buckling. The only significant quantities that depend upon the real force are the stresses and strains. *Thus, the Orpheus tubing forces model works in effective force. The effective force is converted to real force only for stress calculations and output purposes.*

One question that is often asked: Does the bottom hole pressure or the well head pressure try to force the CT out of the hole? The same question can be asked another way: When pushing pipe in against pressure, Does the wellhead pressure multiplied by the cross sectional area force need to be snubbed against or does the pressure at the bottom end of the pipe need to be snubbed against?

To answer this question assume point A in the above analysis is at the surface. The real force in Eq 7 is a function of the bottom of the pipe. However, the real force in Eq 11 is a function of the pressure at the top of the pipe! When the buoyant weight is being used to calculate the weight of the pipe, as is usually the case, the wellhead pressure should be used to calculate the snubbing force.

Furthermore, since the TFM calculation is performed "segmentally" from the bottom of the CT to the surface, a boundary condition or starting condition is required at the bottom of the CT. Consider Figure 3:

1. If the end of the CT is closed, the real force F_R (x=0) = $P_{iB} A_i - P_{oB} A_o$. From the definition of the effective force, F_E(x=0) = F_R(x=0) - $P_{iB} A_i + P_{oB} A_o$. Substituting for the real force yields, F_E (x=0) = 0.

2. If the end of the CT is open, the real force F_R (x=0) = $P_{oB} (A_i - A_o)$. Now from the definition of the effective force and the fact that $P_{oB} = P_{iB}$ for an open tube gives, F_E (x=0) = 0.

Real Force versus "Weight"

The real force is calculated by rewriting Eq 12 to be:

$$F_R = F_E + P_{iA}A_i - P_{oA}A_o \qquad \textbf{Eq 14}$$

Consider the diagram shown in Figure 4.

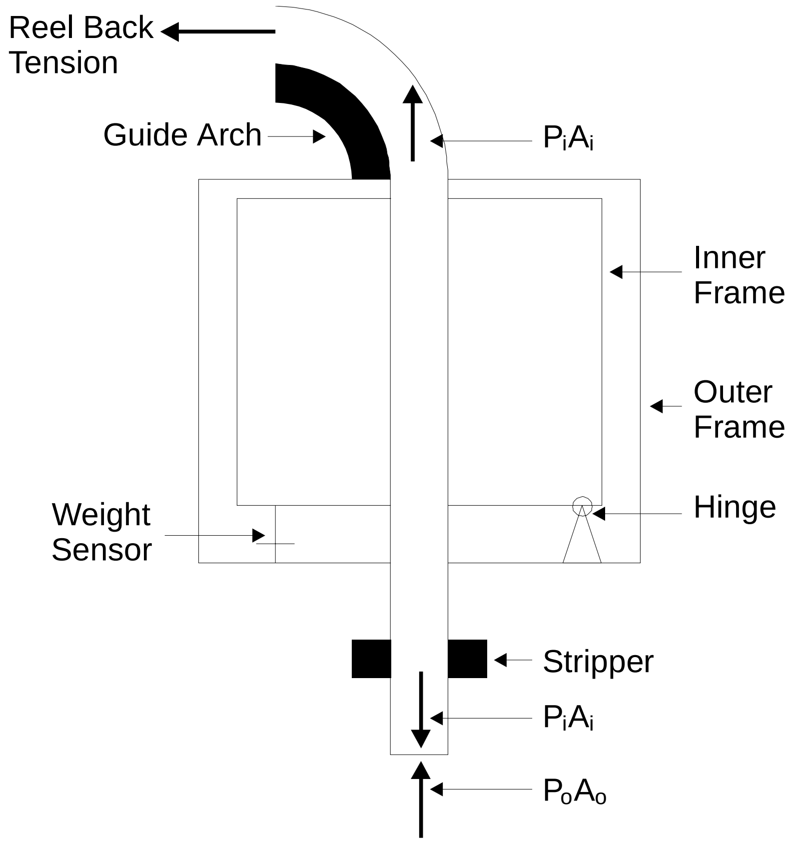


FIGURE 4 Forces at surface

The real force just below the stripper can be calculated using Eq 14. Recall that it is this real force that must be used for stress calculations. The stripper causes the effective force to change such that the effective force above the stripper is reduced by the amount of the wellhead pressure times the cross sectional area, plus or minus the stripper friction depending upon the direction of movement. This can be written as:

$$F_{E-AboveStripper} = F_{E-BelowStripper} - P_{o-whp}A_o \pm F_{F-Stripper} \qquad \textbf{Eq 15}$$

Since P_{oA} is zero above the stripper, the real force above the stripper is the effective force plus the internal pressure times internal area. Thus:

$$F_{R-AboveStripper} = F_{E-BelowStripper} - P_{o-whp}A_o + P_iA_i \pm F_{F-Stripper} \qquad \textbf{Eq 16}$$

It is this real force above the stripper which must be used in the stress calculation. (It should be remembered that the real axial forces calculated in the Hercules module do not take these additional factors into consideration.) Also, this force is different from the force measured by the weight indicator, typically known as the “weight”. The weight is affected by the forces acting above the injector and thus the weight is:

$$Weight = F_{R-AboveStripper} - P_i A_i - RBT \quad \text{EQ 17}$$

where RBT is the reel back tension.

Capstan or Belt Effect

Assume that a section of CT is in tension when it passes around a curve in a well. The tension causes the CT to be pulled against the inside of the curve. The greater the tension, the greater the radial load pushing the CT against the casing. This radial load causes the friction with the casing to increase. This increased friction is known as the “**capstan effect**” or “**belt effect**”.

The same argument can be made if the CT is in compression. Now the CT is pushed against the outside of the curve in the well. Again, additional friction forces are generated which must be considered in a tubing forces calculation.

Thus, any curvature in a well, either in the inclination or the azimuth directions, causes additional friction which adversely affects the movement of the CT into and out of a well. Later we will see that there are cases where curvature is beneficial.

Sinusoidal Buckling Load

Imagine a straight CT string is being pushed into a straight horizontal casing. As the length of CT pushed into the casing increases the force required to push it increases. This force is equal to the total weight of the CT string in the casing multiplied by the friction coefficient. As the length increases the weight increases and thus the force required to push it increases. For the initial distance the CT remains straight, lying nicely in the “trough” formed by the bottom of the casing.

Once the force required to push the CT reaches a certain amount (load), the CT will begin to “snake” in a sinusoidal fashion back and forth across the bottom of the casing. This “certain amount” is referred to as the “**sinusoidal buckling load**” or sometimes the “snake buckling load.” In drill pipe TFMs this is often referred to as the “critical buckling load.” However, there is nothing “critical” about this type of buckling. It does not prevent the CT from moving further into the well. The period of the sine wave is very large (usually 30 to 100 ft), and of course its amplitude is no greater than the ID of the casing. Thus the bending that is occurring is trivial. Orpheus does not even calculate when the sinusoidal buckling load is reached, since it has no impact on the tubing forces calculation.

Helical Buckling Load

Continuing to push the CT into the casing continues to increase the force required to push the CT. The first portion of the CT will still be lying straight in the casing. The second portion, which has an axial load greater than the sinusoidal buckling load, will be lying in a sine wave in the bottom of the casing. Again, a certain load is reached at which the CT begins to form a helix inside of the casing. This load is referred to as the "**helical buckling load**." Again, this load isn't critical. The period of the helix continues to be large, and no significant bending stresses occur in the CT material. However, at this point the tubing forces calculation changes. Helical buckling itself does not prevent the CT from going further into the well. However, as the helix is pushed into the casing there are additional wall contact forces due to the helix. These wall contact forces increase the friction with the wall of the casing.

Lockup

The additional wall contact forces and thus additional friction forces increase as the axial load applied to the CT increases. Now the CT has 3 distinct sections. First there is a straight section up to the point where the sinusoidal buckling load is reached. This is followed by a section which is buckled into a sine wave, until the helical buckling load is reached. Finally there is a section of the CT which is buckled into a helix. It is only this third, helical section in which the additional wall contact forces are being generated.

These wall contact forces increase faster than the rate of increase of the axial load and eventually a "vicious circle" is created in which the additional axial force required to overcome friction increases faster than the applied axial load. This point is referred to as "**helical lockup**." It is not possible to push the CT further into the casing once helical lockup is reached, no matter how much axial load is applied.

The original lockup calculation used in Orpheus (Lockup 1.0) did not take into consideration helical buckling, but rather was based on the yield strength of the CT material. Lockup was determined to occur when any additional force on end would cause the CT stresses to exceed the yield limit of the pipe. Usually this required setting down enough weight with the injector to yield the CT at the surface, which is unrealistic.

The new lockup calculation (Lockup 2.0) is a more sophisticated model which approximates the depth/force combination at which the wall contact forces resulting from helical buckling begin to overwhelm the applied axial load. Specifically, lockup is now defined to occur when a large increase in set down weight causes only a very small increase in force at the end of the tool (downhole force). Figure 5 shows the relationship between the downhole force and the set down weight at a specific depth. Although set down weight and downhole force are treated as positive quantities in the graph and in this discussion, in reality they tend to be compressive forces and hence negative.)

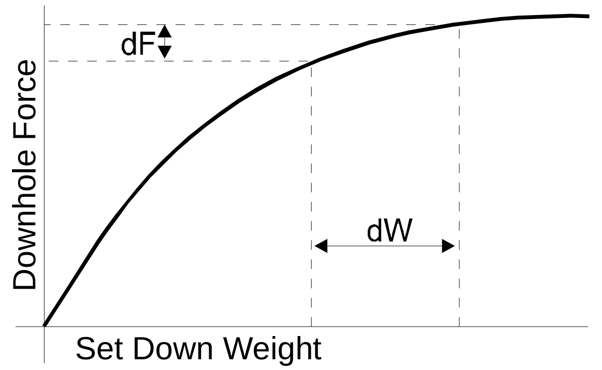


FIGURE 5 Downhole force vs. set down weight

In Figure 5, dF is the change in downhole force, and dW is the corresponding change in set down weight. The weight transfer is the slope, dF/dW. If the weight transfer is less than an arbitrarily designated percentage, then the CT is considered to be locked up.

Effect of Curvature on Helical Buckling Load

The above theory applies to straight CT in a straight hole. Now let's consider what happens if the hole is not straight. Imagine the CT lying in a curved casing. The axial load applied to the CT causes it to "seat" itself in the "trough" formed by the casing. As the axial load increases, the radial load pushing the CT into the seat increases. Thus, the axial load required to cause the CT to pop out of the seat and form a helix is much greater than the helical buckling load for a straight hole.

Increasing the helical buckling load delays the onset of helical buckling, and thus delays the onset of lockup. Thus it could be argued that curvature in the well is beneficial. However, the belt effect caused by the curvature increases the friction. In most cases CT can be pushed further into a straight hole than into a curved hole.

Residual Bend

The above theory applies to straight CT. However, the bending that occurs to the CT at the reel and at the guide arch causes residual stresses in the CT material, which causes the CT to be bent when not in tension. This "**residual bend**" causes lockup to occur more quickly.

Orpheus handles residual bend by assuming that the CT behaves as though it were straight. However, the friction coefficient for RIH is increased to account for residual bend. The typical friction coefficient of 0.2 is increased to 0.3, for RIH only. The increase of coefficient of friction for running in hole accounts for the additional wall contact forces due to residual bend.

Stress Calculations

Orpheus has two stress calculations. By default, Orpheus uses the von Mises stress calculation. This calculation combines the axial stress due to the force on the tubing with the hoop stress caused by external and internal pressure and the radial stress caused by internal pressure, to calculate the combined stress at the inside surface of the CT. Note that for the stress calculation the real force, F_R, must be used. F_R is calculated from F_E using Eq 12 solved for F_R. For more details on how the von Mises stress is calculated see the Hercules module of Cerberus. CTES recommends that the von Mises stress be used.

If the user chooses to turn von Mises stress calculation off, Orpheus only calculates the axial stress. This is simply the real axial force in the CT divided by the cross-sectional area. The axial stress is provided only to allow the user to see this major component of the total stress by itself. The von Mises stress can be turned off under Options, Preferences.

Another component of stress which the user can choose to include in either the von Mises or the axial stress calculation is the additional axial stress due to the helical buckling. By default this stress is not included because it is a very localized stress and does not tend to cause CT failures. This stress component can be included under the Options, Preferences menu.

When the CT is being rotated by an applied torque at the surface or downhole end, the CT string will tend to twist about its longitudinal axis. This twist causes shear stress to occur in the planes of the circular cross-sections and in the longitudinal radial planes. In this case, Orpheus uses a form of the von Mises stress calculation which includes the shear stress term in addition to the three principal stresses discussed above.

Pressure Calculations

The pressure values used in Orpheus are calculated from user inputs for fluid density and flow rate. Currently, the hydraulics model only supports single-phase liquids; however, in the future this model will be extended to include multi-phase fluids and gases. In the case of flowing liquids, the pressures calculated include the frictional pressure loss component resulting from contact with the pipe and casing walls.

Model Equations

Basic Equation

As was described previously, the Orpheus model begins a calculation for the CT string at one position in the well: the bottom end of the string. The effective force and torque calculations are performed for each successive "segment" of the CT up to the surface. *Note that the string segment discussed here has nothing to do with the string segments in String Manager.* The length of a segment varies depending on variations in wall thickness, hole diameter, fluid density inside and outside the CT and well geometry. The maximum segment length can be set by the user, but usually it defaults to 100 ft. The basic differential equation pair[1], which is integrated over the segment is:

$$\frac{dF_E}{ds} = W_B \cos\theta \frac{d\gamma}{ds} + \mu \frac{dF_N}{ds} \cos\beta \quad \text{and} \quad \frac{dT_F}{ds} = r\mu \frac{dF_N}{ds}\delta$$

Eq 18

where

$$\frac{dF_N}{ds} = \sqrt{\left(F_E \sin\theta \frac{d\gamma}{ds}\right)^2 + \left(F_E \quad \frac{d\theta}{ds} + W_B \sin\theta\right)^2}$$

Eq 19

and

$$\delta = \begin{cases} -1, & \text{nonzero torque is applied to non-rotating CT} \\ \sin\beta, & \text{otherwise} \end{cases}$$

Eq 20

This equation is similar to Eq 4 except that it includes the additional friction due to the capstan effect. Note that if the curvature terms $d\gamma/ds$ and $d\theta/ds$ are zero and the internal and external pressures are zero (no fluids), Eq 14 with Eq 15 included becomes the same as Eq 4.

Effect of Fluid Flow

The flow of fluid in the CT and in the annulus around the CT produces two types of forces which must be accounted for in the equation of axial equilibrium, i.e. Eq 18. First, there is a loss in the normal component of fluid pressure due to frictional contact between the fluid and the CT surface. Second, there is an additional tangential component caused by the shear stresses (or viscous drag) on the CT due to the fluid flow. As a result, it has been shown[4] that the following term, which accounts for both of the fluid flow effects mentioned here, must be added to Eq 18:

$$\frac{dF_{Fl}}{ds} = \frac{2\pi r_o r_c}{r_c^2 - r_o^2}\left(r_o\tau_c - r_c\tau_o\right)$$

Eq 21

Helical Buckling Load

The primary equation[2] for the helical buckling load, ignoring the effect of friction on the helical buckling load, is

$$F_{HB} = -2\sqrt{\frac{2EI}{r_c}}\ \sqrt[4]{\left(F_{HB}\sin\theta\frac{d\gamma}{ds}\right)^2 + \left(F_{HB}\frac{d\theta}{ds} + W_B\sin\theta\right)^2}$$

Eq 22

Mobil has provided CTES with proprietary modifications to this equation which account for the effect of friction on the helical buckling load. Another proprietary equation from Mobil is used for the helical buckling load when the inclination is less than 15 degrees.

Wall Contact Force

Eq 19 is used by Orpheus to calculate the normal force per unit length that the CT makes with the hole wall due to weight and the curvature effect. If the CT is helically buckled, an additional wall contact force must be added to Eq 19 to account for the additional wall contact force caused by the helix. This additional wall contact force due to the helix is given by the following equation[3]:

$$\frac{F_{NHB}}{ds} = \frac{r_c F_E^2}{4EI}$$

Eq 23

The total wall contact force per unit length is found by summing Eq 19 and Eq 23. Orpheus outputs a curve showing these values.

Helix Period and Length Change

The period of the helix is calculated using the following equation[4]:

$$\lambda = 2\pi\sqrt{\frac{2EI}{F_E}}$$

Eq 24

Orpheus uses this equation to calculate and output the period length.

The helical shape of the CT requires that the CT be longer than the section of the well it is in. In most cases the difference in length between the CT and the well section is quite small. Orpheus calculates this length difference using the following equation derived from geometry:

$$\Delta L = L\left[\sqrt{\left(\frac{2\pi r_c}{\lambda}\right)^2 + 1}\ - 1\right]$$

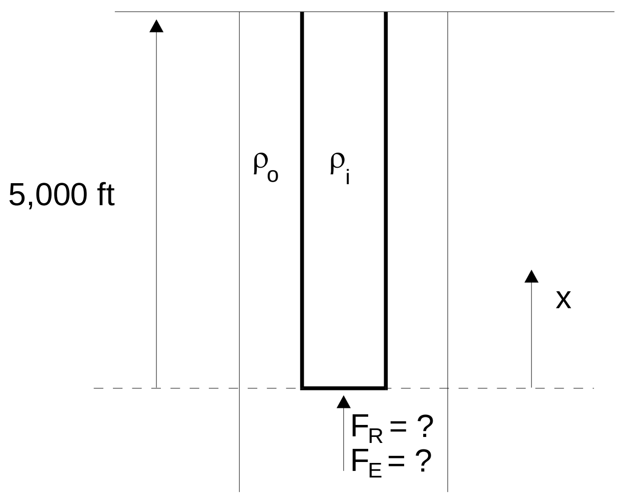
Eq 25

Calculation Examples

The following examples show calculations for the real and effective force.

Vertical Well Example

Consider a CT string of outer diameter 1.5” and thickness 0.109”, the CT string is hanging in a vertical well of 10,000 ft. Let the fluid density in the CT and the annulus between the CT and completion be 8.5 lb/gal (i.e. water of density 63.58 lb/ft^3). Let the CT be closed at the down hole end. The weight per unit length of the CT is 1.623 lb/ft.



Therefore the real force at the end of the CT is $F_R = P_i A_i - P_o A_o$, the internal and external pressures at the CT end are governed by the hydrostatic pressure in the CT and annulus around the CT at the depth in question.

F_R (x=0) = ρ_o g h A_o - ρ_i g h A_i = 1,050.54 lbf

From the definition of the effective force, Eq 14, $F_E = 0$.

The buoyed weight, per unit length, of the CT = 1.413 lbf/ft, from Eq 10.

From Eq 13, the effective force at the surface
F_E (x=5,000 ft) = W_B X = 5000 W_B = 7,064 lbf

Consider two cases:

Case 1. Let the WHP, the circulating pressure, the stripper friction and the reel back tension be equal to zero. Then the real force at the surface = 5,000 W_B, from Eq 10, thus the surface weight as the CT is run in and pulled out of the well is a linear function of the amount *L* of the CT run into hole and equal to 1.413 *L*.

Case 2. If the WHP = 5,000 psi, the stripper friction force = 300 lbf, the reelback tension is equal to 500 lbf while running in hole and 800 lbf while pulling out of hole, then from Eq 16 and Eq 17, the variation of surface weight as the CT is run in hole (RIH) and pulled out of hole (POOH) is:

$W_{RIH} = W_B L$ - WHP A_o + Stripper Friction Force - RBT_{RIH}

= -1971 lbf at 5,000 ft

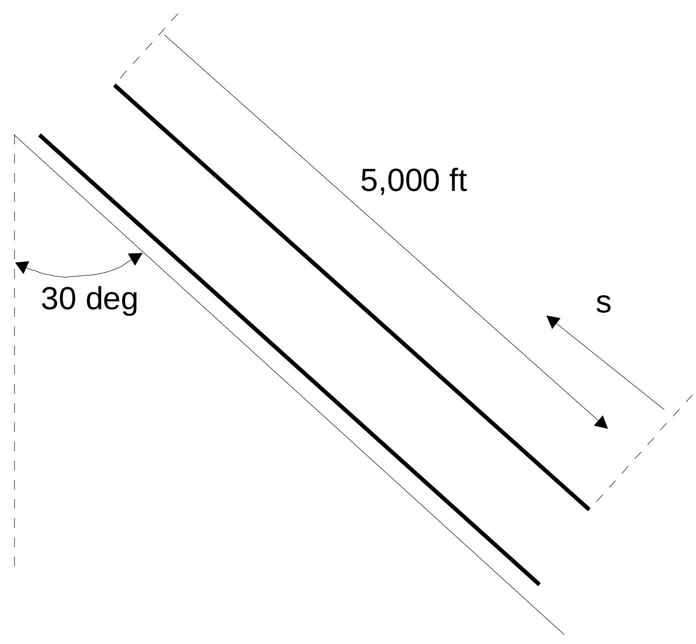
$W_{POOH} = W_B L$ - WHP A_o - Stripper Friction Force - RBT_{POOH}

= -2871 lbf at 5,000 ft

As the CT is being snubbed against the WHP force, the effect of WHP is to decrease the surface weight by a constant amount. Similarly the effect of the reelback tension is to decrease the surface weight.

Inclined Well Example

Consider the same CT geometry as in the example for a straight well. The CT is now run in and pulled out of a well that is inclined at an angle, θ = 30 degrees. Again, let the CT be buoyed by fluid of density 8.5 lb/gal in the CT and in the annulus around the CT and completion. Let the coefficient of friction between the CT and completion be 0.25 for RIH.



Force equilibrium (or Eq 18 with θ = constant and γ = 0) gives:

$$\frac{dF_E}{ds} = W_B \cos\theta \pm \mu W_B \sin\theta$$

where s is the measured depth along the well.

This equation can be integrated to give the effective force as a function of measured depth, noting that the effective force at the downhole end of the CT is zero (if the CT is open or close ended). Thus, the effective force distribution in the CT string is

$$F_E(s) = \left(W_B \cos\theta \pm \mu W_B \sin\theta\right) s$$

The effective force at surface, given the CT is run in hole to a measured depth, *L* equal to 5,000 ft is:

$$F_E(l) = \left(W_B \cos\theta - \mu W_B \sin\theta\right) L = 1.047\, L = 5235.34\,\text{lbf}$$

So it can be seen by changing the well geometry from a vertical to an inclined well , the surface weight has decreased, while RIH, due to frictional resistance.

Now again if the WHP = 5,000 psi, the stripper friction force = 300 lbf, the reelback tension is equal to 500 lbf while running in hole, then the variation of surface weight as the CT is run in hole (RIH) is:

$$\begin{aligned} W_{RIH} &= \left(W_B \cos\theta - \mu_{RIH} W_B \sin\theta\right) L - WHP\, A_o \\ &\quad + Stripper\ Friction\ Force - RBT_{RIH} \\ &= 1.047L - 9{,}035.73 \end{aligned}$$

Again, the surface weight is a linear function of the amount of CT run in hole, but is offset by the well head pressure, stripper friction and reelback tension.

Furthermore, if the stresses in the CT string are to be examined, the effective force needs to be converted back to the real force. For instance, if we wish to determine the true force and stress in the CT string at a measured depth of 1,000 ft from the surface, while the string is being run in hole at a measured depth of 5,000 ft.

Then the true force= effective force at 1,000 ft
+ internal pressure of the CT at 1,000 ft * A_I
- external pressure of the CT at 1,000 ft* A_o.

The effective force at a measured depth of 1,000 ft is:

$$\left(W_B \cos\theta - \mu_{RIH} W_B \sin\theta\right) 4{,}000 = 4{,}060\ lbf$$

Note we measure from the bottom of the CT.

The internal and external pressure of the CT is $\rho_i\, g$ 1,000 Cos θ and $\rho_o\, g$ 1,000 Cos θ, note 1,000 Cos θ is the true vertical depth of the point at a measured depth of 1,000 ft . Thus, the true force at a depth of 1,000 ft is 3,990 lbf and hence the axial stress in the CT at this point is: 3,990/ (A_i - A_o) = 8,382.4 psi.

Curved Well Example

Consider now a curved well with a constant radius of curvature (equal to R, or constant curvature, $\kappa = 1/R$). It can be shown that for a well with a constant curvature, the differential equation governing the effective force, i.e Eq 18 becomes:

$$\frac{dF_E}{ds} = W_B \cos\theta \pm \mu\left[F_E \frac{d\theta}{ds} + W_B \sin\theta\right]$$, by definition $\frac{d\theta}{ds} = \frac{1}{R} = \text{constant}$

The above equation assume no buckling occurs.

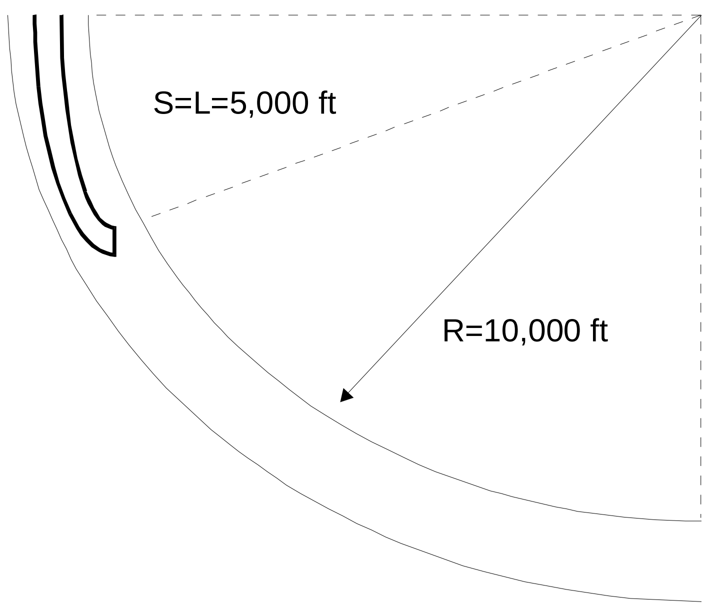
Thus, for running in hole:

$$\frac{dF_E}{ds} = W_B \cos\kappa\, s - \mu\left[\frac{F_E}{R} + W_B \sin\kappa\, s\right]$$

This can be integrated to give, assuming that the CT contacts the bottom side of the well:

$$F_E = \frac{2\mu W_B R}{1+\mu^2} + \frac{W_B R}{1+\mu^2}\left[\left(1-\mu^2\right)\sin\kappa\, s - 2\mu\cos\kappa\, s\right]e^{\mu\kappa s}$$

The solution obeys the condition that $F_E = 0$ at s = 0. Let the radius of curvature R = 10,000 ft.



Let's examine, the effective force, real force, surface weight and stresses of CT with 1.5" OD and 0.109" (W_B = 1.623 lb/ft) thickness being run in hole to a measured depth of 5,000 ft.

For a measured depth of 5,000 ft the true vertical depth is 5,000 Cos(28.65) = 4,387.8 ft. For a measured depth of 1,000 ft the true vertical depth is 1,000 Cos(5.73) = 995 ft. (The angles are obtained from the radius and measured depth being the arc of the well path).

Firstly, calculating the effective force at the surface, given 5,000 ft of CT has been RIH gives:

$$F_E = \frac{2(0.25)(1.432)(10{,}000)}{1+(0.25)^2} + \frac{(1.432)(10{,}000)}{1+(0.25)^2}\left[\left(1-(0.25)^2\right)\sin(28.65) - 2(0.25)\cos(28.65)\right]e^{0.25\left(\frac{5000}{10000}\right)} = 6{,}807.04\,\text{lbf}$$

Now again if the WHP = 5,000 psi, the stripper friction force = 300 lbf, the reelback tension is equal to 500 lbf while running in hole and 800 lbf while pulling out of hole, then the variation of surface weight as the CT is run in hole (RIH) and pulled out of hole (POOH) is:

$$W_{RIH} = 6{,}807.04 - WHP\ A_o + Stripper\ Friction\ Force - RBT_{RIH} = -2228.69\,\text{lbf}$$

Again, lets calculate the effective force at 1,000 ft, the corresponding true force and the stress at 1,000 ft:

F_E (MD = 1,000 ft) = 5,050 lbf

F_R = 4,840 lbf

Thus the axial stress at 1,000 ft in the CT = 10,168 psi.

Nomenclature

A_i = cross sectional area of the inside of the pipe - in^2

A_o = cross sectional area of the outside of the pipe - in^2

E = Young's Modulus - psi

F_A = axial force component - lbs

F_E = effective force - lbs

F_{HB} = helical buckling force - lbs

F_N = normal force component - lbs

F_{NHB} = normal force component due to helix - lbs

F_R = real force - lbs

F_{RF} = frictional resistance opposing rotational motion - lbs

I = moment of inertia - in^4

L = length of well segment - ft

ΔL = amount CT segment is longer than well segment due to helix - ft

P_{iA} = internal pressure at point A - psi

P_{oA} = external pressure at point A - psi

P_{iB} = internal pressure at the end (point B) - psi

P_{oB} = external pressure at the end (point B) - psi

r_c = radial clearance between CT and hole wall - in

s = axis along length of CT

T_F = torque - ft lbs

W_B = buoyant weight of the pipe - lb/ft

W_S = weight of the steel pipe - lb/ft

X = length of pipe below point A - ft

β = velocity vector angle - radians

ξ_I = "density" of the fluid inside the pipe - psi/ft

ξ_o = "density" of the fluid outside the pipe - psi/ft

γ = azimuth angle - degrees

θ = inclination angle - degrees

λ = period of helix - ft

τ_c = shear stress term on the outer radius of completion

τ_o = shear stress term on the outer surface of the CT

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