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Trajectory and Window Width Prediction for a Cased Hole Sidetrack using a Whipstock

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Abstract

This paper describes a computer program developed for predicting the trajectory of a cased hole sidetrack created using a three-mill assembly and a multi-ramped whipstock. The motivation for developing this program was field evidence that mills sometime built inclination faster than intended that could cause fatigue failures or sticking of drill string components, and other times fell back into the original well, causing an unsuccessful sidetrack.

The computer program developed to predict the trajectory of the mills uses the BHA analysis method proposed by Jiazhi to analyze the angle building behavior of the three-mill assembly during sidetracking.

The results indicate that the three-mill assembly extends the useful window length beyond that created with a single mill, and that there is no tendency for the mills to prematurely build angle, suggesting that instances of an excessive build rate are not related solely to the BHA and whipstock designs.

Introduction

Sidetracking out of an existing wellbore is a specific application of directional drilling[1]. Sidetracking is typically done to bypass an obstruction (fish) in the original borehole, to reuse the existing well, or to explore for additional producing horizons in adjacent sectors of the field. Nowadays, sidetracking is also done to develop multiple wells from the existing borehole for more economically developing fields, especially in offshore environments.

Sidetracking involves deviating the well trajectory from an existing cased wellbore at a pre-decided depth below the surface or below the sea floor in an offshore environment. This deviation may be performed by using either a whipstock and a mill assembly or a section mill followed by a bent-sub and a mud-motor assembly. Cased hole sidetracks using whipstocks and mill assembly are the specific focus of this research.

A typical whipstock is an inclined ramp, usually having an inclination of two to three degrees from the axis of the well that can be permanently or temporarily set inside the existing casing. Sidetracking is a process wherein a bottomhole assembly having a mill attached to its lower end rides on this inclined ramp to deviate the well trajectory from the existing one as the whipstock forces the mill into the casing wall thus cutting through the casing. The opening cut through the casing is called a "window".

The focus of this study is related to trajectory and window profile predictions for a specially designed whipstock and mill assembly. This particular whipstock has multiple ramps having different ramp inclinations. Also, the mill assembly consists of three mills of the same diameter at specified distances from each other. Fig 1 shows the multi-ramped whipstock and the trimill assembly. As shown in Fig 1 the multi-ramped whipstock consists of two fifteen degree ramps, two three degree ramps and a straight ramp having no inclination at specific positions from the top of the whipstock. The trimill assembly consists of three mills of the same diameter at specified distances from each other as shown in Fig 1. The lowermost mill is called the lead mill (LM). Placed above the LM is the follow mill (FM) and the top most mill is called the dress mill (DM). All of the mills are designed to cut both the casing and the rock. The FM and DM are intended to help extend the window length and subsequently increase the length of the major axis of the elliptical sidetracked borehole[2, 3, 4]. The mills are either dressed with high-grade tungsten carbide cutting material or polycrystalline diamond inserts as cutters. To ensure that the mills preferentially cut the casing and not the whipstock, the whipface is made of hardened steel.

The trimill assembly rides on the multi-ramped whipface creating a lengthened hole in the casing called the 'window' as shown in Fig 2, and progressing into the surrounding cement and rock formation, resulting in a deviated well trajectory of approximately three degrees. Fig 2 also depicts the sidetracking operation using the multi-ramped whipstock and trimill assembly.

In certain sidetracking instances in the field, the mill assembly was observed to leave the whipface and move entirely into the formation rather than following the face of the whipstock for its entire length. In other cases, the mill assembly was observed to cut downward along the casing as soon as it reached the end of the whipstock face. These scenarios raised questions regarding the actual trajectory and the resulting curvature of the sidetracked hole. This increased inclination or the curvature of the deviated trajectory, in the sidetracked section, increased the potential of downhole tubulars failing due to excessive stress or fatigue or sticking in this particular section.

This paper describes a method to predict the trajectory of the sidetracked borehole based on the tendency of the trimill assembly to build, hold or drop inclination, as it progresses on the multi-ramped face of the whipstock. The paper also involves the calculation and prediction of the casing window width and height, and the length of the major axis of the elliptical borehole created by the trimill assembly.

Directional Drilling Model for Trajectory Prediction: The Jiazhi Model

Field evidence of the trimill assembly prematurely leaving the face of the whipstock raised concerns regarding the trajectory and the resulting borehole curvature. These instances increased the potential of downhole tubulars failing due to excessive stress, fatigue, or sticking in this particular section. Hence, the focus of this study was to predict the trajectory path, cut by the mill assembly, by analyzing the tendency of the bottomhole assembly (BHA) to build, hold, or drop the angle of inclination.

The BHA that the Jiazhi model[5] analyzes might consist of drill collars alone or a combination of drill collars, MWD (measurement while drilling) tools and stabilizers or drill collars with a mud motor along with a MWD tool. The Jiazhi model calculates the side force and its direction at the bit for a given arrangement and placement of stabilizers in the BHA. Therefore the BHA analysis, done by the model, can be used to predict the tendency of that BHA to increase, decrease, or hold the borehole inclination, based on the magnitude and direction of the side force calculated to be acting on the bit.

The model calculates the length of tangency and moments developed on the stabilizers which are used for calculating forces that act on the bit, as a function of the clearance between the stabilizers and the borehole wall, and the arrangement of stabilizers, assuming that the stabilizers contact the low side of the inclined borehole. The Jiazhi model uses the Timoshenko method[6] of beam analysis to calculate the moments developed on the stabilizers and the length of tangency of the BHA with the borehole wall. The analytical solution for calculating the length of tangency and the moments developed on the stabilizers differ with the number of stabilizers in the BHA considered for analysis.

The length of tangency of the drill string and the moment developed on each stabilizer are calculated by an iteration process. The iteration process is as follows.

1. A length of tangency is assumed to begin with, typically with a starting value of about 45 ft, which helps calculate the moments on the stabilizers.
2. From the calculated moments at the stabilizers, the tangency length is re-calculated.
3. An average value of the assumed and calculated length of tangency is taken as the next guess, and the process returns to step 1 until the assumed length of tangency in step 1 matches with the calculated tangency length in step 2.

The side force and its direction at the bit are calculated with the help of the predicted tangency length and the moments from the above iteration. The magnitude and the direction of the side force determines the inclination building, holding or dropping tendency of that particular BHA.

Overview of the Trajectory and Window Prediction Program

The computer program applies the above mentioned BHA theory developed by Jiazhi for predicting the trajectory and window profile cut during the sidetracking operation. This analytical theory models the behavior of the trimill assembly as if it were a two stabilizer directional drilling assembly. The Jiazhi model considers the bending of the body (mandrel) of the trimill assembly and the bending of the drill string above it as it rides on the multi-ramped whipface, cutting the casing and deviating the borehole. This model was further developed to calculate the side forces on each of the mills. The program applies the Jiazhi model at discrete finite increments of depth as the trimill assembly rides on the multi-ramped whipface, and calculates the side forces developed on each mill at every incremental step. Based on these calculated side forces a new position for each of the mills is predicted, which is then validated in reference to the predicted forces developed on each mill and its relative position with respect to the whipface and the borehole wall created by the preceding mill. The trajectory and the width of the window cut by each mill is then calculated geometrically based on the validated positions of each of the mills and plotted at every increment of depth during the sidetracking operation.

Design of the Computer Program

The following subsections describe the concepts and the specific methods used and the assumptions made in creating the simulator for predicting the trajectory cut by the trimill assembly during the sidetracking operation using whipstocks.

Conceptual Application of Directional Drilling Models to Sidetracking

The simulator[7] uses the Jiazhi model to calculate the forces developed on the lead mill, which acts as a basis for calculating the forces on the follow mill (FM) and the dress mill (DM). The moments developed at the FM and DM must be determined, as described by the Jiazhi model, to calculate the side force at the Lead mill (LM). The forces developed on each of the mills are calculated using the calculated moment on each of the mills and the tangency length. The governing equations for calculating the side forces on the FM and DM are described in the preceding sections.

The simulation begins when the program calculates the contact point of the LM with the casing on the first fifteen-degree ramp. At this point, it is assumed that no other mill contacts the casing. The simulator uses the slick BHA (BHA with no stabilizers) solution for calculating the length of tangency and the side forces on the lead mill. When the FM touches the casing and starts cutting it the solution changes from a slick BHA to a one-stabilizer BHA. The length of tangency and the developed forces are calculated using the Jiazhi solution for one-stabilizer. As the LM rides on the multi-ramped whipface, the DM is observed to touch the casing and the problem changes from a one-stabilizer system to a two-stabilizer BHA system calculation. The solutions for the slick, one-stabilizer, and two-stabilizer bottom hole assembly are separately mentioned and illustrated by the Jiazhi model.

Description of the Structure and Working of the Simulator

The flow diagram shown in Fig 3 gives an overview of the structure and working of the simulator. The details of each step are explained in the following sections. A summary of the steps followed by the program are as follows:

1. At each incremental position of the lead mill, the simulator uses the Jiazhi solution to calculate the length of tangency the side force on the lead mill, and the moments developed on the mills as a function of the relative positions of the mills with respect to the lead mill. The simulator uses the Jiazhi solution for no-stabilizer (slick BHA), one-stabilizer or two-stabilizer bottom hole assemblies, depending on the number of mills contacting the casing and/or the rock.
2. The simulator then calculates the side forces developed on the mills, as a function of the moments calculated by the Jiazhi solution
3. The simulator then validates the position of the mills relative to the calculated side forces on each mill.
4. The simulator then records and plots the position of each mill and the window width cut by the mill.
5. The position of the lead mill is increased by 0.05" in the vertical direction along the face of the multi-ramped whipstock based on the calculated side force and its direction, and the program returns to step 1.

The force calculations on the mills, the validation criteria and trajectory and window width calculations are explained in the following subsections.

Calculation of the Forces on the Mills

The method used to solve for the forces developed on each mill is based on the structural analysis approach for calculating forces at the supports for indeterminate beams.

In Fig 4**,** support A represents the LM, support B represents the FM and support C represents the dress mill. The side force developed on the FM due to the moment M_1 developed on the FM and M_2 developed on the DM is calculated as described by the following equations.

Reaction force at support A (LM) is given by

$$F_A = \frac{q_1 l_1}{2} + \frac{M_1}{l_1} - \frac{P_1 e_1}{l_1} \qquad (3)$$

Taking the sum of lateral forces to be zero, for beam AB gives,

$$F_{BA} = q_1 l_1 - F_A \qquad (4)$$

Then, the force calculated at B considering beam BC is

$$F_{BC} = \frac{q_2 l_2}{2} - \frac{M_1}{l_2} - \frac{P_2 e_2}{l_2} + \frac{P_1 e_1}{l_2} + \frac{M_2}{l_2} \qquad (5)$$

The total force calculated at support B is given as

$$F_B = -F_{BA} - F_{BC} \qquad (6)$$

Where, l_1 is the length between support A (LM) and B (FM), l_2 between supports B (LM) and C (DM). Here, q_1 is the uniformly distributed load over length l_1 acting at angle α (overall inclination of the borehole), P_1 is the average axial load acting at point B and P_2 be the average axial load acting at point C. Also, e_1 and e_2 as referred to in equations 3 and 5 are the displacements of points C and D with point A.

As F_B is the reaction force calculated at support B, the direction of the force exerted by the beam on support B is given as the negative value of the force calculated by equation (6), which is ($-F_B$).The above calculation is repeated for calculating the force at support C that represents the DM.

Calculation of the New Position of a Mill (Vectorial Approach – 'The θ -rule')

Fig 5 shows a side force F2 developed on the mill. As WOB is applied in the axial direction, the resultant angle developed due to force F2 is given by (1)

$$\theta = \tan^{-1}(F2/WOB) \qquad (7)$$

Because the mills are intentionally designed to cut in all directions, a reasonable assumption is that the direction taken by the mill is the same as that of the force applied on the mill, as implied by equation (1).

Therefore the new incremental movement of the mill in the x-direction as shown in Fig 5 is

$$\Delta x = \Delta y \tan(\theta) \qquad (8)$$

Equation (1) and (2) constitute the "θ -rule", where ΔY is the increment of travel in the axial direction of the trimill assembly 0.05" below the earlier position and ΔX is the increment of travel in the lateral direction.

Validating the Position of and Force on the FM and DM

As the FM and DM progress in accordance to the "θ-rule", the lateral forces on them decrease as the eccentricity between the centers of the mills and the lead mill decreases. The fact that the mills cannot cut the casing or the rock when the forces on them are negative initiated the need for a validity criterion. To counter this problem, a minimum threshold force of 100 lbs was assumed to be required for the FM and the DM to cut the rock and/or the casing. Further, either the FM or DM was assumed to stop cutting the casing or rock in the lateral direction, when the lateral force developed on it fell below the minimum threshold value. Likewise, the position of the FM or DM must fall between the whipstock and the previously cut rock, if the force calculated on the mill was zero. Furthermore, the FM and DM were assumed to contact the adjacent inclined face of the whipstock if the force calculated on them were negative.

The trimill assembly with the drill string above it can be visualized as being represented by the string of a bow and arrow, which requires a higher side force if the string is deflected further. The FM and DM were assumed to cut the rock and the casing if the forces on them were equal to or greater than the minimum threshold force required. If the forces on the FM and DM drop below the minimum threshold force, the simulator iterates for a valid solution by decreasing the lateral distance of the mill from the casing inner wall, at that particular y position until the force on the mill equals the minimum threshold force or otherwise gives an acceptable solution based on the criteria mentioned below.

If F2 is the calculated side force on the FM or the DM and a 100lbs force was assumed to be the minimum threshold force required to cut the casing and the rock, then an acceptable solution for the positioning of, and force, on a mill would be:

1. If F2 >= 100, then the mill is assumed to cut the casing and/or the rock.
2. If 100 > F2 > 0, then the mill is assumed to touch and ride on the previously cut rock without being able to cut it.
3. If F2 = 0, then the mill is assumed to fall in-between the whipface and the previously cut rock without transferring load to any surface.
4. If F2 < 0, then the FM/DM is assumed to be in contact with the whipface.

A flowchart illustrating an iterative method for finding a valid solution is shown in Fig 6**.** In Fig 6 X_{FM} is the distance from the center of the FM to the lower inner wall of the casing. OD_{FM} is the diameter of the FM and γ is the overall inclination of the trimill assembly riding on the multi-ramped whipface. Xrock and Xwhip are the horizontal distances of the previously cut rock and the inclined face of the whipstock from the lower inner wall of the casing, respectively. The functions Incr (X) and Decr (X) are the increase or decrease in X_{FM} required to cause the forces on the mill, so as to validate the position and force on the mill. The actions a_1, b_1, c_1 and d_1 are the set of rules for predicting the positions of the FM and the DM at the y_{i+1} increment, depending on the existing conditions for a valid solution, at the y_i step. These actions are described in the following section.

Predicting Mill Positions at the Next Depth

Once the positions of the mills are validated, the criteria for the mill positions at the next increment of depth, shown in Fig 6 as a1, b1, c1 and d1 are described as follows.

1. a_1: If at y_i increment, the program selects a valid position of the FM/DM on the whipface, with negative force on it then, at the y_{i+1} increment the assumed position of the FM/DM is on the whipface.
2. b_1: If at y_i increment, the program selects a valid position of the FM/DM between the whipface and the previously cut rock with the mill not contacting any surface, with a zero force on it, then at the y_{i+1} increment, FM/DM are assumed to have a progress so as to keep the eccentricity between the LM and the FM/DM constant or in other words, have the same increment in the positive x-direction as that of the LM.
3. c_1: If at y_i increment, the program selects a valid position of the FM/DM touching the previously cut rock, with a positive force of less than 100 lbs on it then, at the y_{i+1} increment, FM/DM are assumed to continue to follow the previously cut rock surface.
4. d_1: If at y_i increment, the program selects FM/DM position as cutting the casing and/or rock and the force on the mill is equal to or greater than 100 lbs, then at y_{i+1} increment, the progress of the FM/DM is governed by the "θ-rule".

Plotting the Window Width and the Trajectory of the Validated Positions of the FM and the DM

Once the positions of the FM and the DM are validated with respect to the above criteria, the window width and the trajectory are plotted as follows. At each increment the program records the validated position of the mill relative to the inside lower wall of the casing. This aids in calculating the displacement between the centers of the casing and the mill. The width of the window cut in the casing is the resultant length of the chord due to the intersection of the circle represented by the casing and the circle represented by the mill[7].

The trajectory or the path followed by the mill is also plotted relative to the position of the mill calculated from the lower inner wall of the casing. The innermost and the outermost points of the circle representing the mill is recorded relative to the lower inner wall of the casing and plotted to give the position of the mill and thus define its path at every incremental step of the lead mill on the multi-ramped whipface[7].

Assumptions for Trajectory and Window Profile Program

The following assumptions were made when applying the simulator in this study.

1. The original borehole is straight over the interval from 50ft above the whipstock to the base of the whipstock.
2. The FM and the DM act as stabilizers for force calculations only, but cut the casing and formation depending on the forces developed on them, when predicting the well trajectory.
3. The existing borehole is tilted at an angle 'α' from vertical.
4. A length-weighted average is taken as representing the moment of Inertia I, for the bottom hole assembly (BHA) above the trimill assembly.
5. A 5000 lb weight on bit is applied for the entire sidetracking process.
6. A minimum threshold force of a 100 lb is assumed to be required for the follow mill and the dress mill to cut the casing and the rock.

Outputs of the Simulator

Fig 7 shows the graphical output from a simulation. If the trajectory is defined as the side view of the path cut by the trimill components, then the front view shows the width of the window cut by the mills. It also shows the trajectory and the window width cut by each mill as the trimill assembly rides on the multi-ramped face of the whipstock.

Fig 8 shows the resultant trajectory and window width cut by the trimill assembly. These reflect the maximum extent of the borehole cut by the three mills.

Results of Trajectory Predictions for Selected Sidetrack Operations

The results of applying the simulator to selected sets of well geometries, tool configurations and resistance to sidetracking allows conclusions to be drawn regarding the effects of these variables on the expected trajectory of a sidetrack. To thoroughly understand the effects of these variables on the expected sidetrack trajectory, the results were compared to a base case as explained below.

Base case

As a typical application of the trimill assembly and the multi-ramped whipstock is a sidetrack from the 9 5/8" casing, and was selected as a base case. The results of this case are shown in Fig 7 and Fig 8. The key inputs for predicting the trajectory for this case were as follows. An average value of the WOB of 5000 lbs was used for the entire milling process. This value was also used for trajectory and window profile predictions for all the other casing sizes.

The BHA above the trimill assembly was thought, to play a significant role in the predictions of the trajectory or the build up angle in the sidetracked section and potentially in determining whether the lead mill left the whipface prematurely. The moment of inertia of the components of the BHA can have a significant influence on the directional tendencies of the assembly. The sidetrack prediction for the base case uses a drill collar joint along with the other necessary BHA components above the trimill assembly.

The program was run for an assumed minimum value of 100 lbs side force required for a mill to cut into the rock and/or the casing. The selection of this value is arbitrary, but it is obvious that some side force must be applied to a mill before it will cut any material. Also, the side force is expected to be much less than the axial force, or WOB, because the assembly only cuts 9" to the side versus 250" in depth.

The results for the 9 5/8" casing sidetrack shows that the DM contacts the upper inside wall of the casing while the LM rides on the first three-degree ramp and consequently increases the length of the window for almost five feet above the top of the whipstock.

Sensitivity cases

Casing Size

In order to understand the effects of smaller casing sizes and thickness (or cross sectional areas), a system for 7" casing was analyzed. The trajectory and the corresponding window-widths were predicted for 7" casing and the corresponding size combination of the sidetracking tool (whipstock and trimill assembly). Fig 9 shows the predicted trajectory for 7" casing size sidetrack.

The results indicate behavior similar to that for the 9 5/8" casing sidetrack predictions except for the DM contacting the upper inside wall of the casing while the LM is riding on the straight ramp extending the window length above the top of the whipstock, by 4 ft.

Bottom Hole Assembly

The magnitude of the effects that is caused by using a different stiffness BHA was studied here. In the sidetracking operations, a HWDP (heavy weight drill pipe) is sometimes used instead of a drill collar in the BHA above the trimill assembly. This changes the moment of inertia, I, of the BHA above the trimill assembly, which can potentially change the directional tendencies of the trimill assembly.

This case maintained the same dimensions of the sidetracking equipment except that the drill collar was replaced by a joint of HWDP (heavy weight drill pipe) to observe the change in the predicted trajectory and the corresponding window-width profile.

Fig 10 shows an overlay of the predicted composite trajectories and the corresponding window profile for the bottom hole assemblies of the base case with a drill collar and this case, with a HWDP in the BHA above the trimill assembly.

It shows that the major axis, length of the elliptical hole predicted by the program for the HWDP case was smaller than that predicted using a drill collar in the BHA above the trimill assembly. The predicted trajectory also shows that the trimill assembly should build angle slower with a HWDP in the BHA above the trimill assembly, but the difference is insignificant, as observed in Fig 10.

Force Required to Side Cut the Rock and Casing

The intent of varying the value of this parameter was to observe the predicted angle building behavior of the trimill assembly for harder formations. This effectively allowed the simulation to account for rock strength, in terms of the force required for the mills to side cut as an input variable. Logically, the trimill assembly should experience increased bending if a larger side force is required to cause the mills to side cut. The goal was to observe the predicted trajectory and whether the trimill assembly would be more or less likely to leave the whipface, when milling harder formations. Also, this case was intended to give an insight into the effects of making incorrect assumptions about the magnitude of the threshold force or of milling a much stronger rock. The minimum value of side force selected for this analysis was 600 lbs.

The only variable changed was the side force required for the mills to cut the rock and the casing. Fig 11 shows an overlay of the different maximum trajectories predicted assuming 100 lbs and 600 lbs force required for the mills to cut the rock and the casing.

The results indicate that assuming a higher threshold force of 600 lbs decreases the length of the major axis of the predicted trajectory as compared to the case where only a minimum threshold force of 100 lbs is required to cut the casing and the rock. Also, the predictions show a more rapid dropping tendency of the trimill assembly after the LM passes the end of the multi-ramped whipface if the 600 lbs threshold force applies.

Summary

A computer program was developed that performs the BHA analysis necessary for predicting the trajectory cut by a mill and whipstock assembly used to perform a cased hole sidetrack. The program utilizes the Jiazhi model to calculate the forces developed on the mills, which are then used to predict the path traversed by each mill. Further, the program validates the position of each mill relative to the side forces developed on the mills and the borehole geometry. The program then calculates and plots the position and window width cut by each mill, thus making it possible to observe the borehole cross sectional geometry and length, and the window profile created during the sidetracking operation. The program was run for selected well geometries, tool configurations and resistance to sidetracking in order to understand the effects of these variables on the predicted trajectories. A method was developed to calculate the curvature, expressed as dogleg severity, for a specific pipe diameter, based on an assumed set of contact and tangency points of the pipe with the casing and the predicted borehole trajectory.

Conclusions

1. The Jiazhi model was used to predict trajectories for cased hole sidetracking operations with a mill and whipstock that satisfactorily match qualitative expectations based on physical lab test results for these sidetrack systems.
2. The simulator for all the selected cases predicts an enlarged window length and an elliptical borehole geometry, which was expected based on physical tests conducted by Smith Services.
3. The simulator predicts an overall dropping tendency for the trimill assembly during the sidetracking operation. Therefore it shows a strong tendency for the lead mill to follow the face of the whipstock and then to drop angle below the whipstock.
4. None of the cases studied show any tendency for the lead mill to prematurely leave the face of the whipstock. Hence, some other factor must be contributing to the lead mill prematurely leaving the whipface. It may be due to the interaction of the mill shape with the casing window and/or the rock or cement in the casing-hole annulus.
5. The trajectory predictions provide an appropriate basis for evaluating the actual dogleg severity associated with a sidetrack using a whipstock

Recommendations

1. The same value of the side force was assumed to be required by the mills to cut both the rock and the casing. The program should be improved by being modified to incorporate different side forces required for the mills to cut rock and the casing.
2. Representative values of the side force required for a mill to cut a known strength rock and casing must be obtained from instrumented shop tests of the sidetracked systems for use in the improved programs.
3. The validity of the predictions using this program should be verified. The borehole geometry and window width should be predicted for the conditions in the instrumented tests and compared to the actual measured

Acknowledgments

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References

1. Bourgoyne, Millheim, Chenvert, and Young: Applied Drilling Engineering, SPE Textbook Series, Vol. 2, 1991, USA.

2. Greg Miller, Charles Dewey, and James Saylor, Smith Intl. Inc.: “Sidetracking in a Single Trip,” SPE/IADC 37665 presented at the 1997 Drilling Conference, Amsterdam, The Netherlands, march 4-6,1997

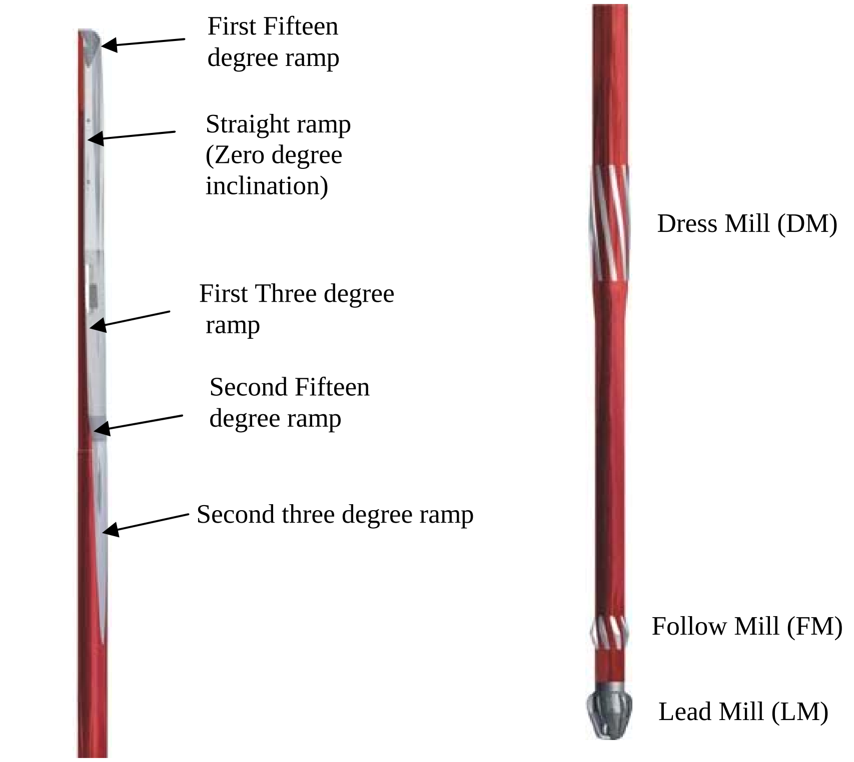
3. Praful C. Desai and Charles H.Dewey, “Milling Variable Window Openings for Sidetracking,” IADC/SPE 59237 presented at the 2000 Drilling Conference, New Orleans, Louisiana, Feb 23-25, 2000.

4. Charles H. Dewey, Ronald D. Childers, “Planning for Successful Window Milling Operation,” SPE 49255 presented at the 1998 SPE Annual Technical Conference, New Orleans, Louisiana, Sep 27-30,1998.

5. B Jiazhi: “Bottomhole Assembly Problems Solved by Beam Column theory,” SPE 10561 presented at the 1982 SPE International Meeting on Petroleum Engineering, Beijing, March 19-22, 1982

6. Theory of Elastic Stability, Timoshenko and S.P Gere, McGraw-Hill Book Co. Inc., New York City, 1936.

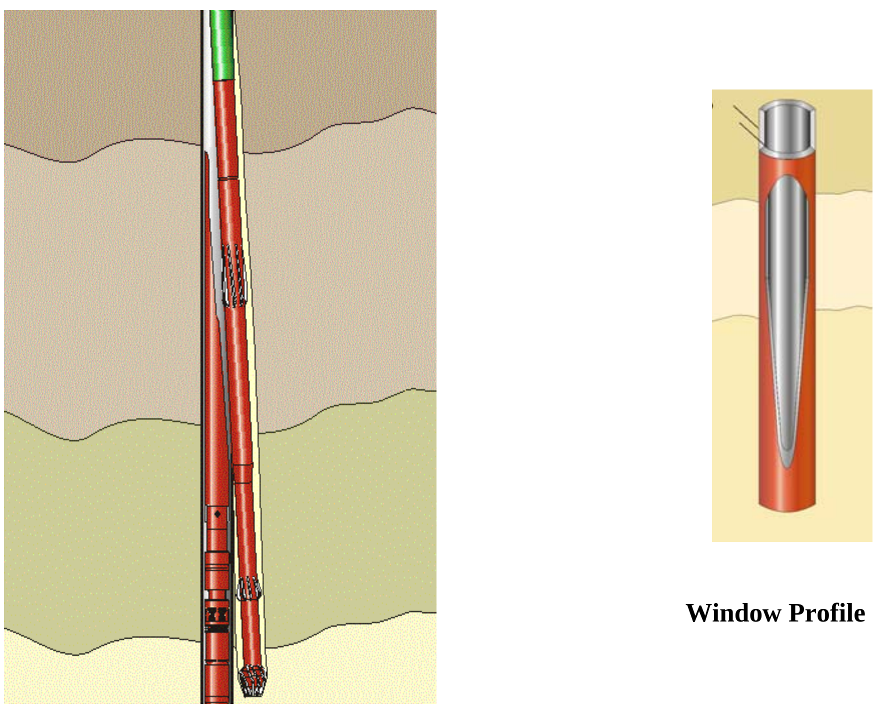
7. Patil, H.P.: Trajectory and Window Width Prediction for a Cased Hole Sidetrack Using a Whipstock, MS Thesis, Louisiana State University (2004).



Multi-ramped Whipstock

Trimill Assembly

Fig1- Multi-ramped Whipstock and Trimill Assembly



Window Profile

Sidetracking Operation

Fig 2- Schematic of the Sidetracking Operation and the Resultant Window Profile

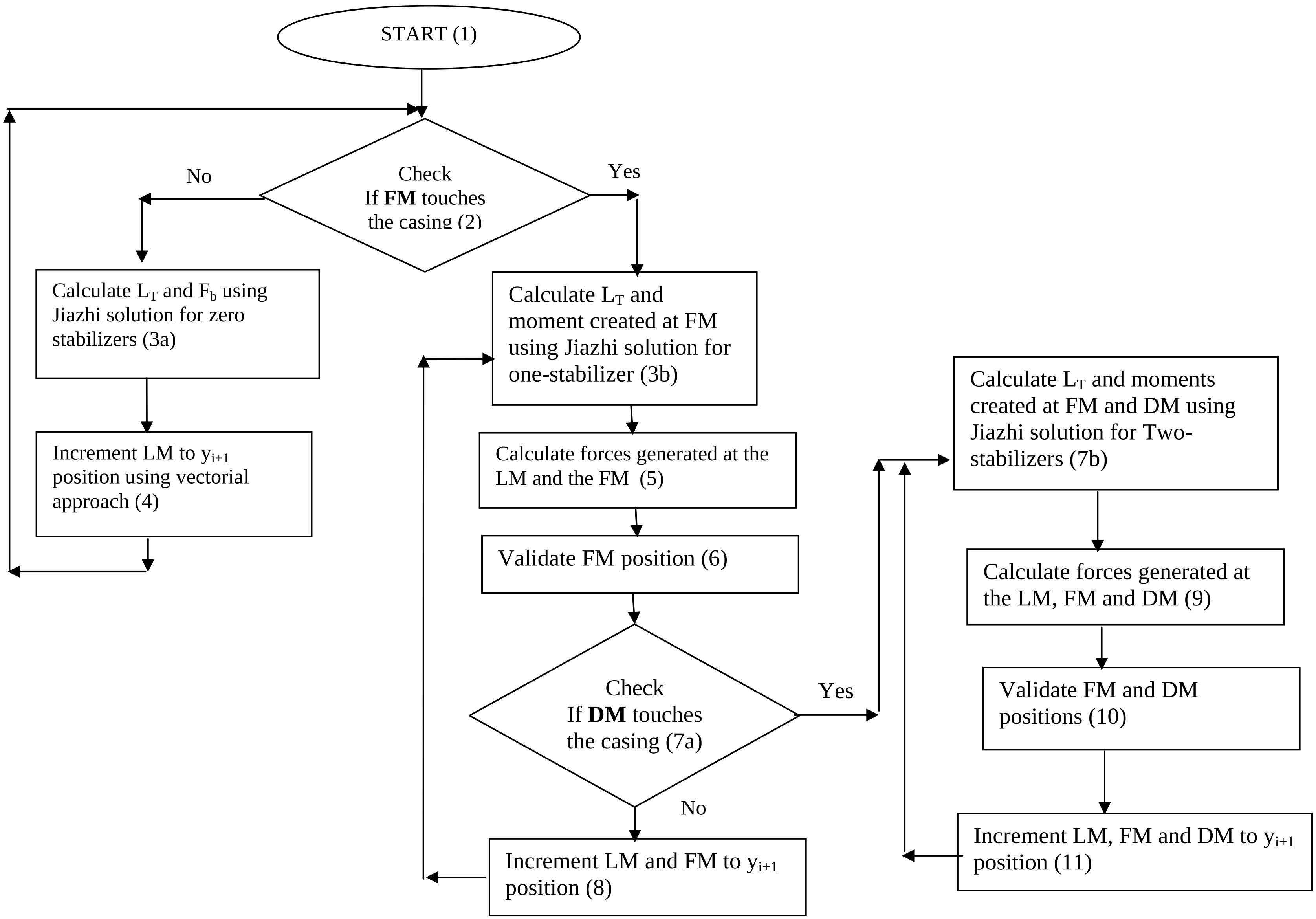


Fig 3- Structure and Logic of the Simulator

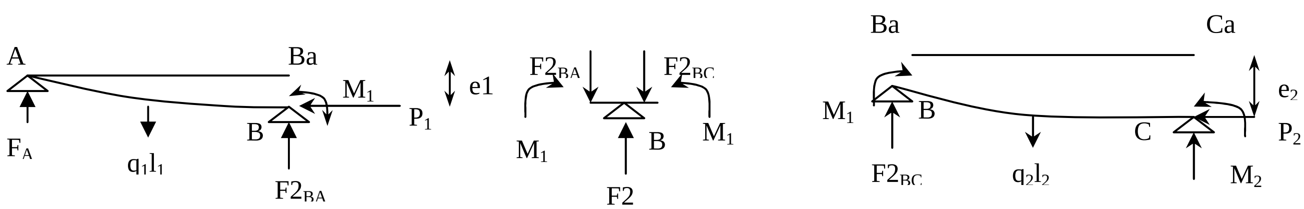


Fig 4- Force Calculation at a Support

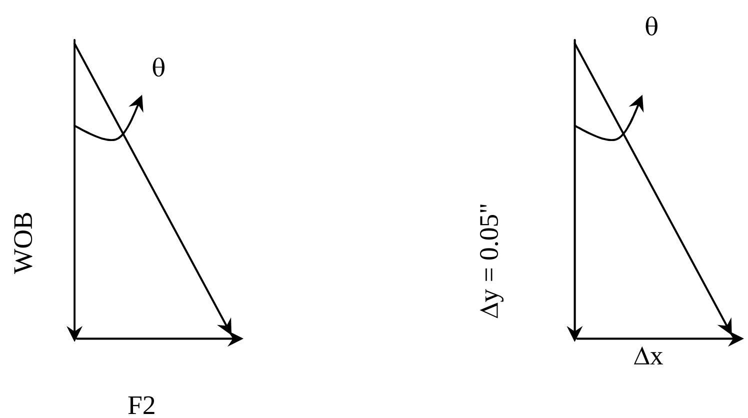


Fig 5- Vectorial Approach (θ- rule)

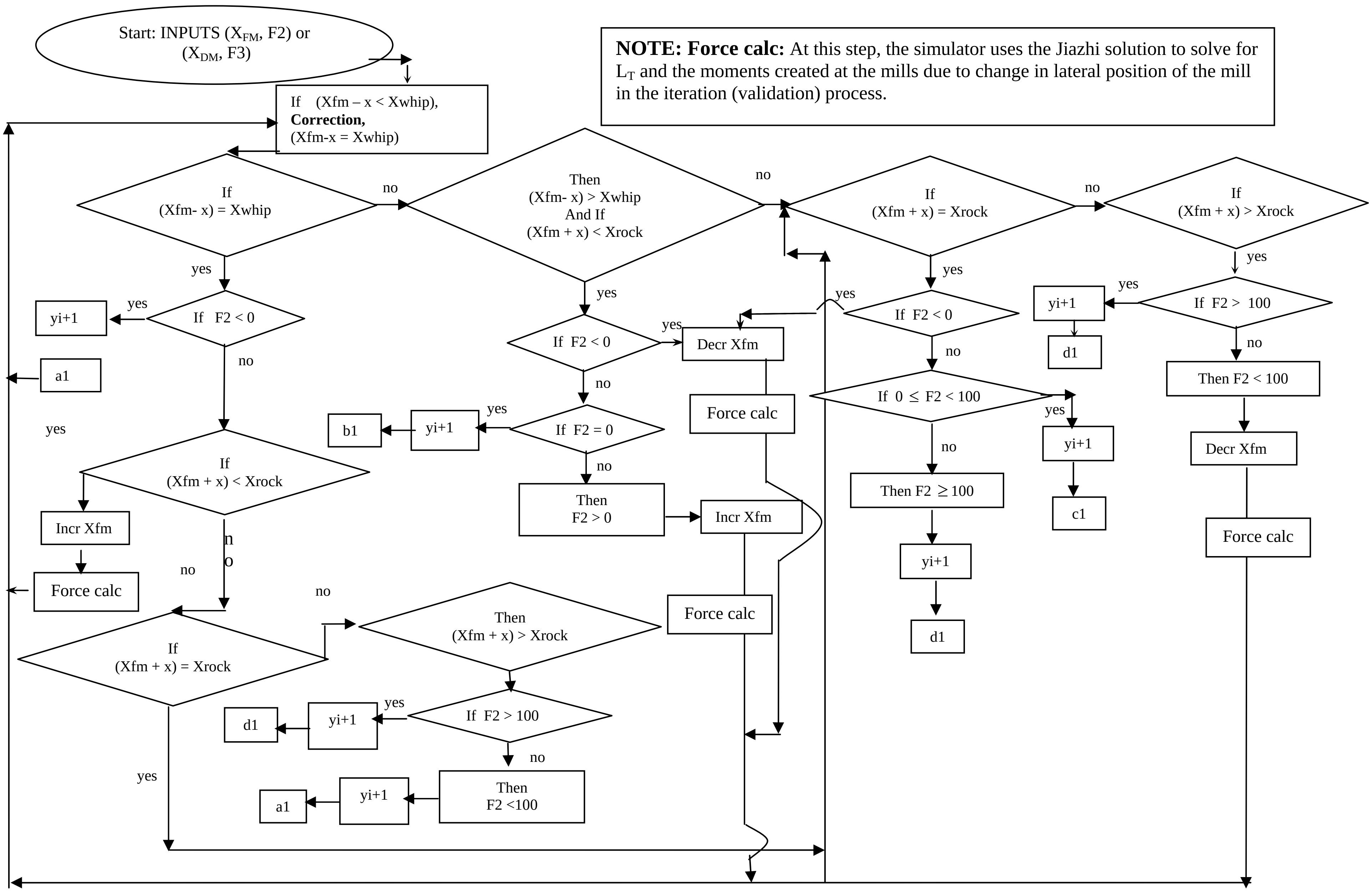


Fig 6- Program for Validation of Position Relative to the Forces Developed on the mills

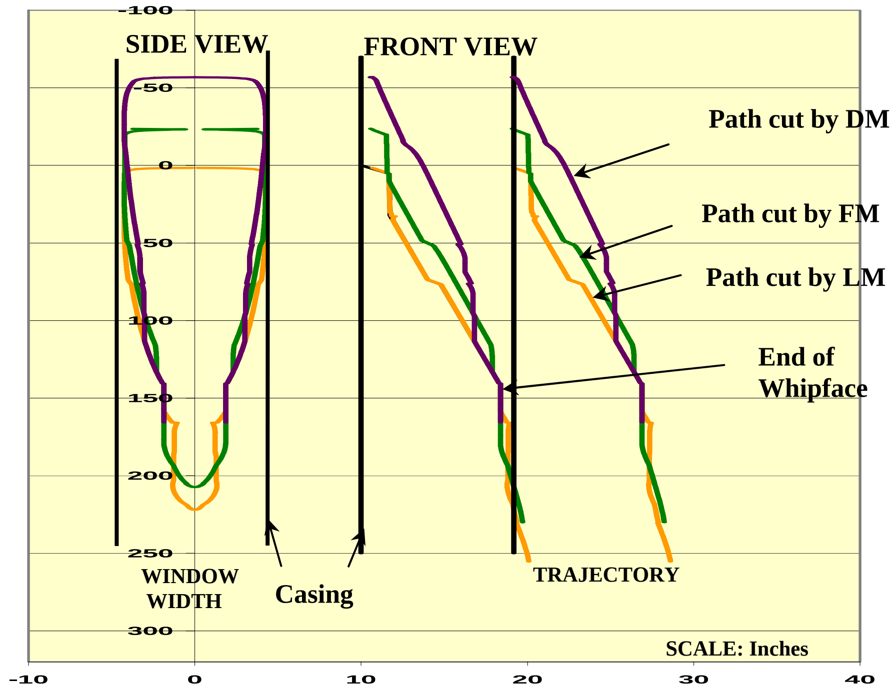


Fig 7- (Simulator Results) Trajectory and Window Width Cut by Each Mill

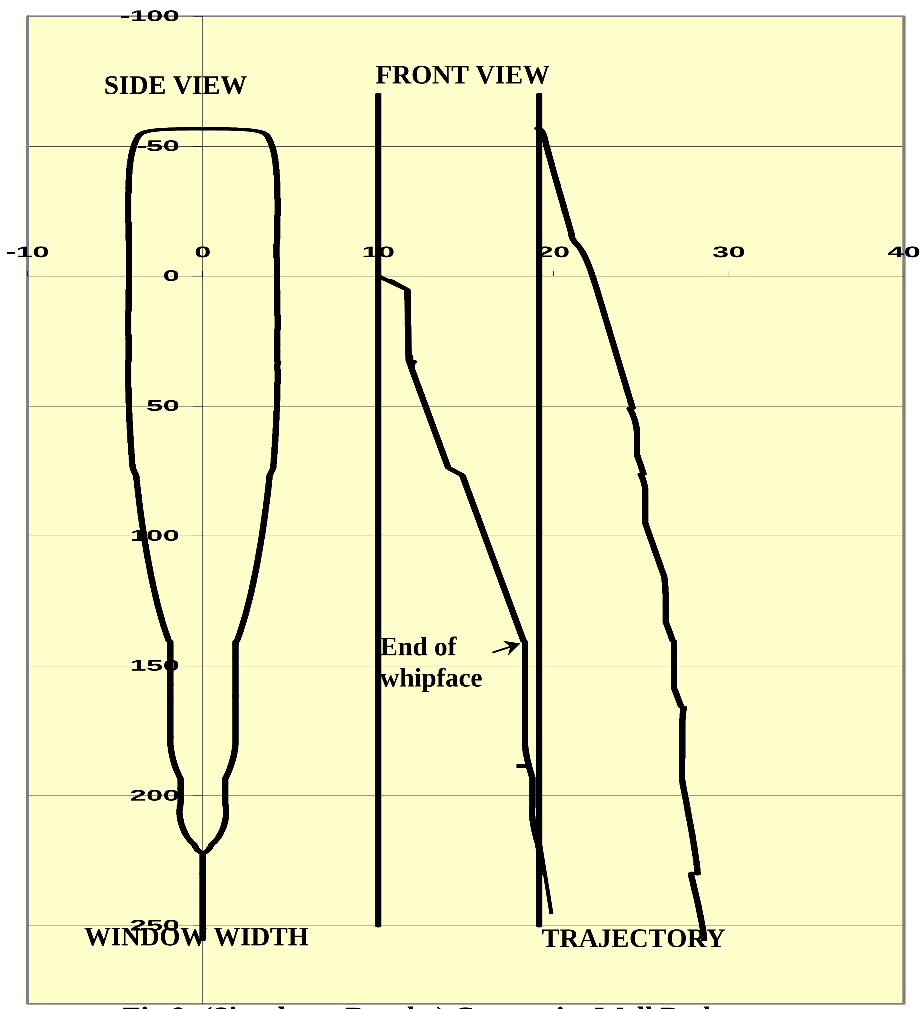


Fig 8- (Simulator Results) Composite Well Path

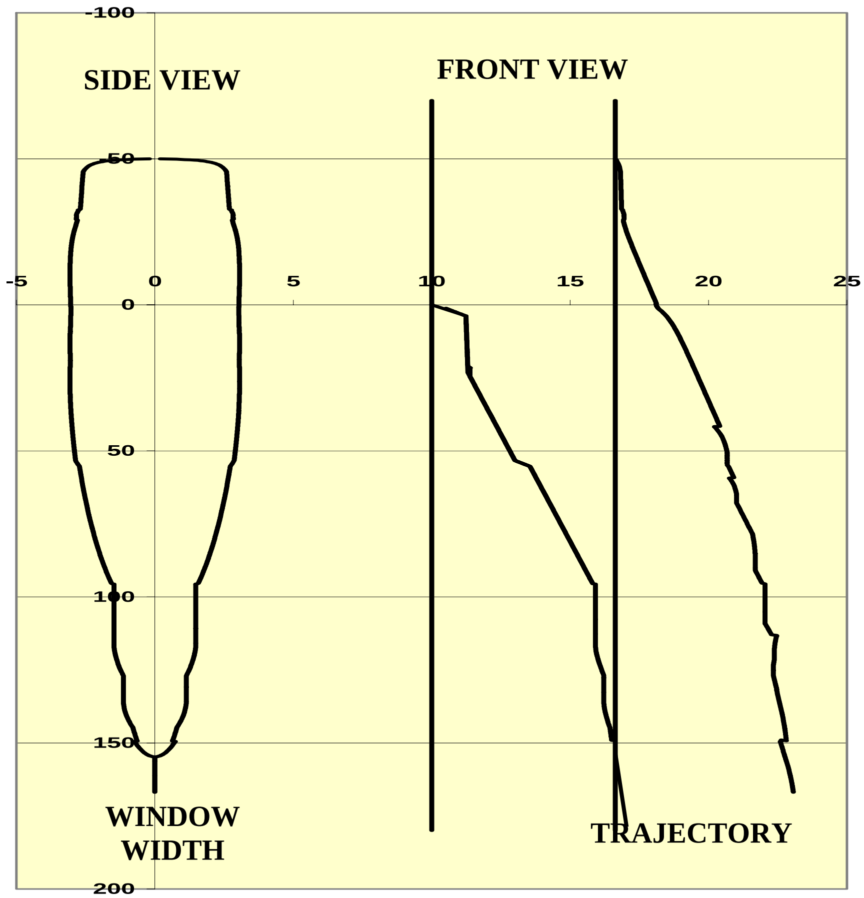


Fig 9- Composite Trajectory and Window Widths Cut by the Mills for 7” Casing Sidetrack System

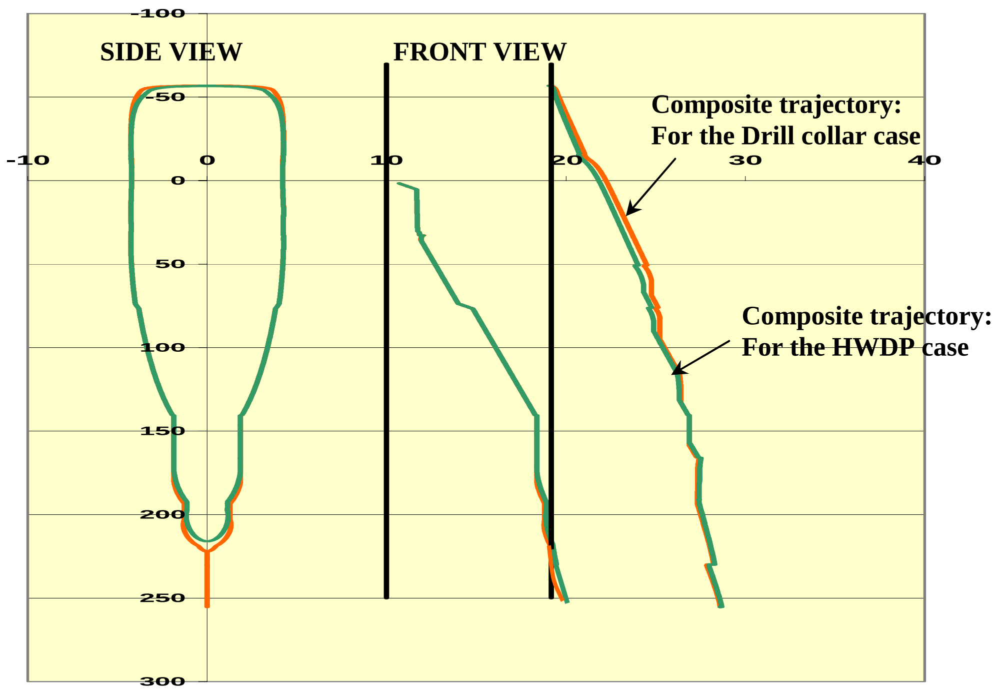


Fig 10- Overlay of the Different Composite Trajectories and Window Widths for Bottom Hole Assemblies Having Drill Collar and HWDP

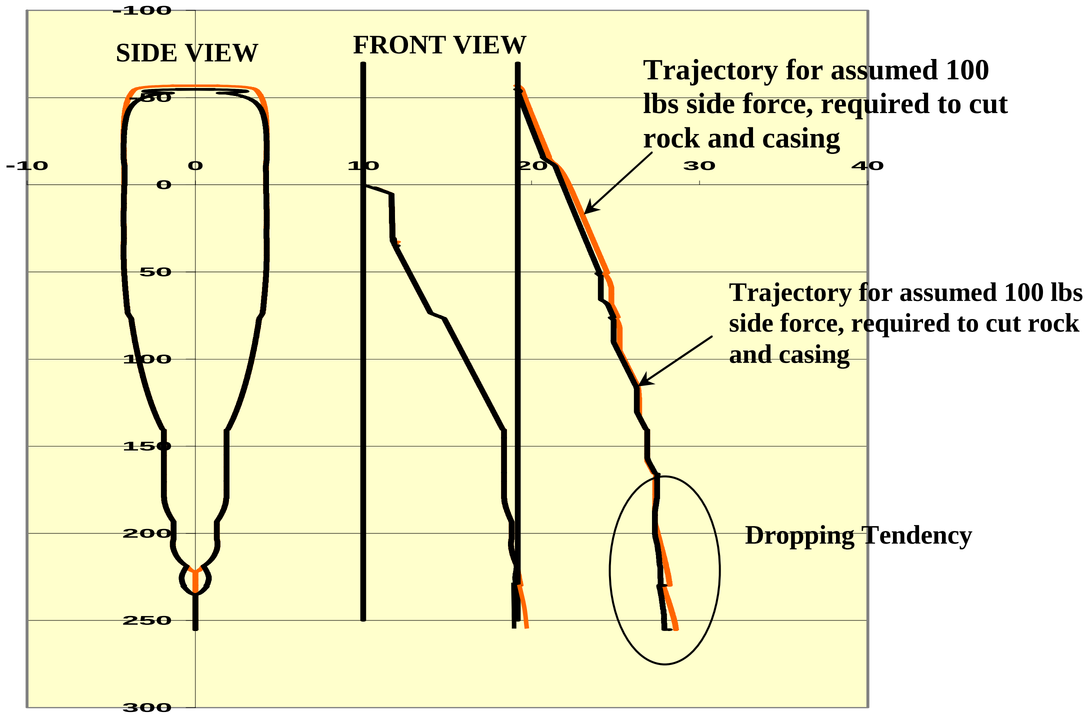


Fig 11- Overlay of Composite Trajectories and Window Widths assuming 100 lbs and 600 lbs Force Required for the Mills to Cut the Rock and the Casing.