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On 3D FE Analyses For Understanding & Designing the Processes of Casing-Window-Milling for Sidetracking From Existing Wells

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Abstract: Little is explained about the process of casing window milling for sidetracking due to lack of analytical method for its mechanical characteristic. In this paper, 3D FE models are established using the commercial finite-element software ABAQUS/Explicit to make simulation analysis for two key stages of the process including the initial stage of casing milling and the stage of full-gauge casing window milling. The models involve the effects of main drilling parameters such as reaction force, torque, speed, feed rate per revolution, and milling angle. The calculation results verify the capability and advantages of 3D FE simulation for the process of casing window milling.

Keywords: finite element analysis; milling; casing window; sidetracking; drilling

1 Introduction

Faced with the prospect of plugging and abandoning (P&A) more and more mature wells, operators may opt to sidetrack from an existing well for a new target zone. Various types of sidetracking methods have been developed to meet this demand. Regardless of how the methods and tools change, the basic principle is that a whipstock is set in the main wellbore, and then BHAs are run to mill out the casing. The key technology is how to make the milled window in accordance with the design by controlling drilling parameters.

The process of casing window milling is very complex. It is difficult to use a simple model to interpret it. For a long time, some improvements are made first through experiences and then by a large number of experiments. A lot of time and money must be spent for every experiment which is very difficult. Therefore, it is

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meaningful to simulate and recognize the roles of various parameters during the casing milling process by using the computer simulation technology.

There are many kinds of casing window milling methods (Nazzal *et al.*, 1996). Different shapes of casing window can be milled by changing the inclination of whip stock (Desai and Dewey, 2000). The whipstock incorporates a 15 degree ramp at the top (Fig. 2 A-B). The mill also has a short gauge contact above the taper. As the weight is applied it, the mill engages with the casing and creates a quick cut out (Fig. 1 A-B). The window of casing is shown in Fig. 3(From A to B).

The initial 15 degree ramp (Fig. 2 A-B) is followed by a zero degree ramp (Fig. 2 B-C), meaning the whipstock face is vertical. The window (Fig. 3 B-C), which is already a full gauge window, is elongated as the mill slides along the vertical face of the whipstock.

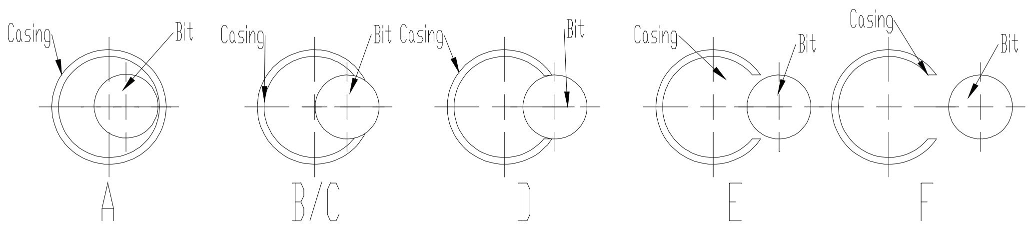

Figure 1: The process of casing window milling

On this whip face, the straight section of the whipstock (Fig. 2 B-C) is followed by a 3 degree or more section (Fig. 2 C-D) which pushes the center of the mill towards the wall of the casing (Fig. 1 B/C). As the center of the mill approaches the wall of the casing (Fig. 1 D), a 15 degree ramp (Fig. 2 D-E) is used to accelerate its course to the outside of the casing (Fig. 1 E). Then, the angle of the whip face is reverted back to the typical ramp angle (Fig. 2 E-F).

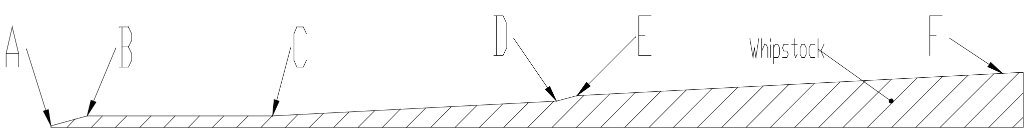

Figure 2: The five ramps of whipstock

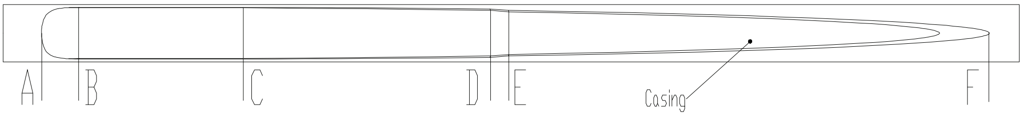

Figure 3: The casing window

2 Finite Element Model

Soo (Soo *et al.*, 2010) , Ozel (Ozel *et al.*, 2011) and Isbilir (Isbilir and Ghassemieh, 2011) have demonstrated the feasibility for the applications of ABAQUS / Explicit in metal-cutting issues through various experimental studies.

The two stages of milling are the successful keys for milling the perfect window when the mill contacts the 15 degree ramp and the vertical ramp. Thus, two FE models are established respectively for the two stages and the 3D models are also developed by using the commercial finite-element software ABAQUS. The models aim to simulate the process of casing window milling and predict the reaction forces & moments throughout the process, the window shape at sides of the entrance and at the exit while taking into account the drilling engineering parameters. Each casing window milling operation is carried out with the use of drilling fluid as the coolant. It is assumed that the mill induced heat is removed by the coolant. Thus thermal issues are not accounted in the model. The overall dynamics are not taken into consideration in the analysis and the mill is modeled as a rigid body.

In this study, interaction between the casing and the mills is modeled by using a Tangential behavior self-contact available in ABAQUS/Explicit. The penalty friction model is used, and a constant friction coefficient of 0.3 is used in the analysis. The two overall FE models are shown in Figure 4 and Figure 5.

3 Constitutive Relation of Casing Material

In order to perform FE simulation of casing window milling process, the Johnson-Cook constitutive realtion (Johnson and Cook, 1983) is used to calculate casing behavior under large deformation.

Parameters in the Johnson-Cook constitutive relation and failure criterion of casing can be got by MTS (Material Test System) and SHPB (Split Hopkinson Pressure Bar) (Xing *et al.*, 2012). The influence of temperature on the material is not taken into account. All parameters of casing material are given in Table 1.

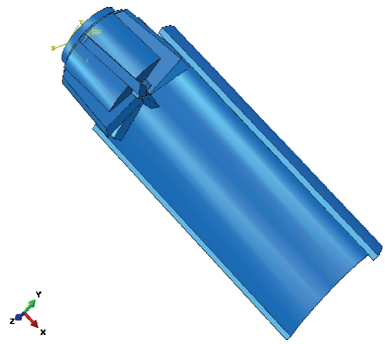

Figure 4: FE model for initial milling stage

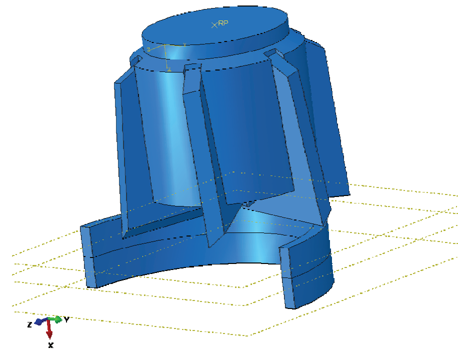

Figure 5: FE model for full-gauge window milling stage

Table 1: Material parameters in the Johnson-Cook model

A(MPa)	B(MPa)	C	n	m	d1	d2	d3	d4	d5
552	1658.4	0.0937	0.95582	0	0.1	0.76	1.53	0.05	-0.84

4 Experiment

The experiment was finished in the Drilling Simulation Laboratory of Dagang Oilfield, China. An 8-1/2" mill (shown in Fig. 6) was used to mill a 9-5/8" casing of N80 grade in the experiment. Experimental torque curve during full-gauge window milling is shown in Fig.7 in which the vertical axis represents the torque and the unit is Nm. It is shown in Fig. 7 that the torque varies between 550Nm∼2,600Nm at this stage. Comparatively, as shown in Fig. 11, the torque obtained by simulation varies between 500Nm ∼1,700Nm at full-gauge window milling stage.The simulation results are consistent with the experimental results to certain extent.

5 Results and Discussion

The initial milling stage and the full-gauge window milling stage are two typical stages in fenestration. The reaction forces and moments on the mill in each stage are very unique. Two FE models are constructed for these two stages.

5.1 The inital milling stage

At the initial milling stage, the focus of engineering applications is on the resultant force of the mill, and then some parameters are dependent on the reaction force, which include the design of the mill, whipstock angle, the BHAs(bottom hole as-

Figure 6: The mill used in the experiment

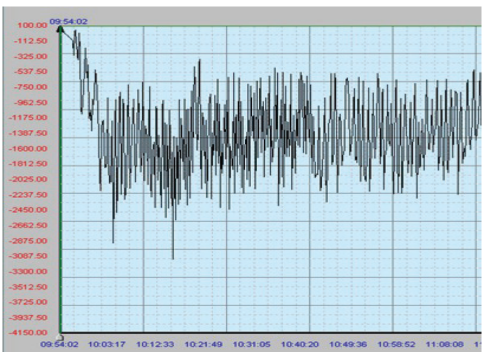

Figure 7: Torque in full-gauge window milling

Figure 8: The window of casing

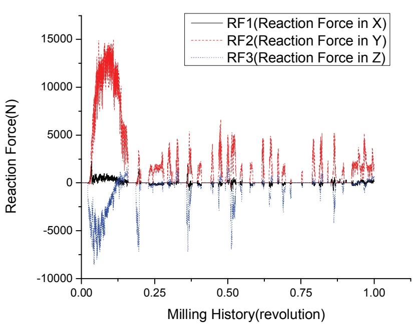

Figure 9: The reaction forces (MA=12°)

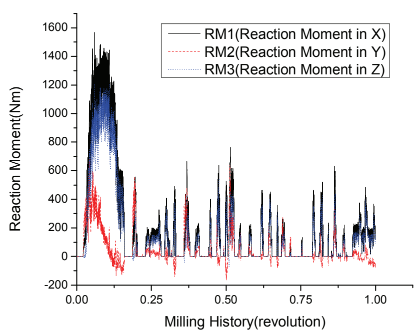

Figure 10: The reaction moments (MA=12°)

sembly), and the appropriate drilling parameters (WOB, torque, rate of penetration, etc.).Through simulation analysis, the reaction forces and torques withstanded by the mill in this process can be calculated. The reaction forces and moments in diferent directions of X,Y,Z are illustrated in Fig. 9 and Fig.10 when the milling angle(MA) is the angle between the center line of mill and casing and equal to 12 degree.

As can be seen from Figure 9, at the initial milling stage, the mill needs to withstand a relatively larger force in the Y-direction which can reach 15,000N. The force in the X-direction is relatively smaller value approximately equal to 1,000N. The reaction force in the Z-direction is rather large, up to 8,000N. As shown in Figure 10, the main torque is along the X-direction, which can reach 1,500Nm. The torque is consistent with the experimental data. It is worth noted that there are also torques in the Y and Z-directions. The torque in the Y-direction can even reach 1,200Nm.

5.2 Full-gauge window milling stage

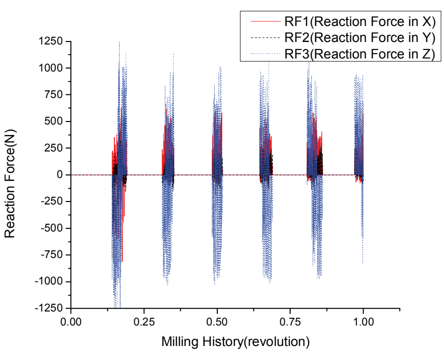

Figure 11: The reaction forces (FPR=0.9mm)

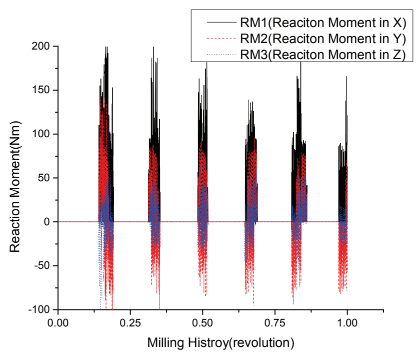

Figure 12: The reaction moments (FPR=0.9mm)

At the full-gauge window milling stage, the mill is smoothly milling the casing window along the oblique orbit. The reaction forces and moments of the mill in the process can be obtained by the FE analysis (Fig.5). The curves of the mill reaction forces and moments are shown in Fig.11 and Fig.12 when the FPR (feed rate per revolution) is equal to 0.9mm. The curves are enlarged in Figures 13 and 14 to understand the magnitudes of the reaction forces and moments.

At this stage, the reaction forces and moments are correspondingly stable. Similarly, the reaction force in X-direction is relatively small(about 600N); the reaction force in Z-direction reaches 1,000N. At this stage, the moment in X-direction is about 220Nm, and the moments in Y-direction and Z-direction are relatively small.

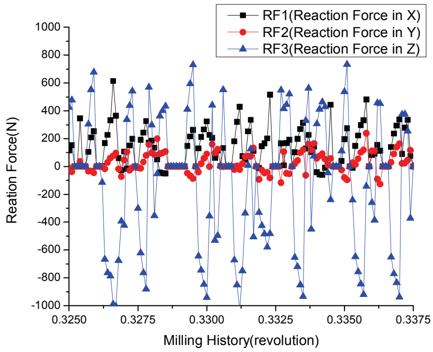

Figure 13: An enlarged view of Figure 11

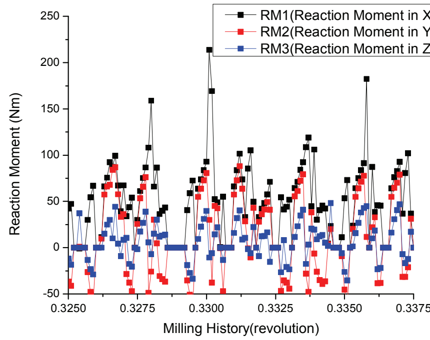

Figure 14: An enlarged view of Figure 12

The greater concern in this stage is the milling speed. Thus, 10 FE models are used to analyze 10 kinds of milling speeds between 0.1mm$\sim$1.0mm, and the maximum values of the reactions and the moments of the mill can be obtained at different milling speeds. The curves are shown in Fig.15 and Fig.16.

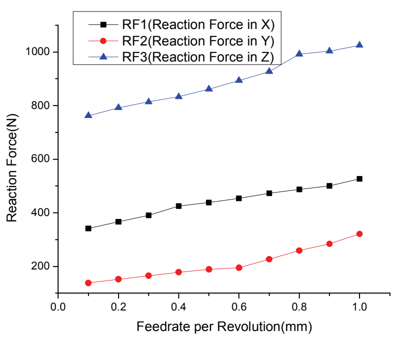

Figure 15: Reaction forces at various FPR

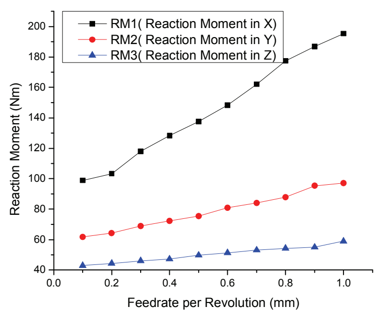

Figure 16: Reaction moments at various FPR

6 Conclusions

1. The dynamic simulation analysis for milling casing window can be carried through the 3D FE model presented in this paper. The complex structure of the mill has been taken into account in the model based on the initial stage of casing milling and the stage of full-gauge casing window milling. The simulation models involve the effects of main drilling parameters such as torque, speed, feed rate per revolution and milling angle.

2. In the process of casing milling, the mill not only withstands the reaction forces and moments in the vertical direction, but also relatively large bending moments in other two directions.

3. At the initial milling stage, it is needed to apply both large torque in X-direction and large force & bending moment in Z direction to the mill.

4. At the full-gauge window milling stage, the feed rate per revolution has relatively large impact on the reaction forces and moments of the mill.

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