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Numerical Analysis and Experimental Validation of a Downhole Stress/Strain Measurement Tool

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***Abstract*—**Real-time measurement of applied forces, like tension, compression, torsion, and bending moment, identifies the transferred energies being applied to the bottomhole assembly (BHA). These forces are highly detrimental to measurement/logging-while-drilling tools and downhole equipment. Real-time measurement of the dynamic downhole behavior, including weight, torque, bending on bit, and vibration, establishes a real-time feedback loop between the downhole drilling system and drilling team at the surface. This paper describes the numerical analysis of the strain data acquired by the measurement tool at different locations on the strain pockets. The strain values obtained by FEA for various loading conditions (tension, compression, torque, and bending moment) are compared against experimental results obtained from an identical experimental setup. Numerical analyses results agree with experimental data within 8% and, therefore, substantiate and validate the FEA model. This FEA model can be used to analyze the combined loading conditions that reflect the actual drilling environment.

***Keywords*—**FEA, M/LWD, Oil & Gas, Strain Measurement.

I. Introduction

In challenging conditions, such as deep-water wells, complex well trajectories, Extended Reach Drilling (ERD) and drilling in depleted reservoirs, a superior understanding of downhole drilling dynamics is key to mitigating vibration and cutting nonproductive time (NPT).The efficient transfer of energy from applied surface drilling parameters is crucial in improving drilling efficiency. Real-time measurements of applied force, like tension, compression, torsion, and bending moments, identifies the transferred energies being applied to the bottom hole assembly (BHA). These measurements help optimize drilling parameters to maximize performance and minimize wasted energy transfer and vibration.

The weight on bit (WOB) is the reaction force applied to the drillbit by the formation in the axial direction and can be controlled by a varying degree of support provided by the rig. The torque on bit (TOB) is the torque exerted on the drillbit by resistance from the formation and can be controlled by varying the torque applied by the motor that rotates the drillstring. In extended–reach applications, modeling of weight-on-bit or drillstring torque is performed to predict directional or vibrational tendencies. However, models cannot fully predict the complex interaction of geological or BHA changes that occurs during drilling, such as hole enlargement or BHA components that become under gauge. Placing the sensors as close to the bit as possible helps to ensure that the correct WOB and torque are applied to the cutting structure. Hole-opening operations require careful control of weight and torque on the bit and reamer to help ensure consistent hole opening.

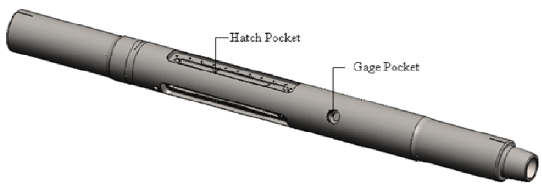

Fig. 1 Basic stress/strain measurement tool layout

Downhole stress/strain measurement tool (Fig. 1) is used to measure WOB, TOB, and bending moment during drilling operation. The tool consists of strain gauges placed in the gauge pockets that measure the strains in longitudinal and transverse directions; these strain readings are further processed to acquire final output in terms of WOB, TOB, and bending moment near the bit. The finite-element model was built to aid the tool calibration for better accuracy. Close correlation obtained between strain values derived from FEA and experimental strains enables the model to be used for further analysis to check the structural integrity of the tool. The succeeding sections elaborate the considerations made while building the FEA model, different loading conditions, and validation of the FEA model.

II. FEA Modeling

The finite-element method (FEM) is a numerical method to solve differential and integral equations, which represent the behavior of physical systems. The method originated as a technique to analyze complex structural systems. The discovery of this method is often attributed to Richard Courant (1943) who used the Ritz Method of variational calculus to analyze vibrational systems. The use of this method in structural (aircraft) analysis was first reported by Turner *et al.*

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in 1956 in *Stiffness and Deflection Analysis of Complex Structures* [1].

The rapid increase in computational power and reduction in computational costs have led to a more extensive use of FEA in various industrial domains. The typical numerical FEA programs that are currently available in the industry are run on personal computers in which models are easy to develop and use. Multiple analyses can be run to refine and improve new conceptual designs. The application of FEA has changed the design processes in other industries; the benefits could be brought to drillstring design and innovation. FE modeling and solutions for the complete drillstring, however, are exceptionally time consuming and complex; consequently, it is limited to drillstring components [3] [4].

The objective of this study is the numerical analysis of the strain data acquired by the measurement tool at different locations for various loading conditions (tension, compression, torque, and bending moment). The measurement tool is a MWD/LWD sensor (Fig. 2) that measures weight, torque, and bending moment on a BHA operating downhole in a well. In addition, the tool also incorporates a vibration sensor that communicates a full suite of vibration measurements. The measurement tool comprises three identical circumferentially spaced wall pockets for situating strain gages. Each gage pocket is connected to the cavity, called a hatch pocket, which encompasses the electronics. There are eight strain gages in each pocket; weight measurements are provided by four axially arranged strain gages (W_1, W_2, W_3, W_4), and torsion measurement is provided by the remaining four strain gages (T_1, T_2, T_3, T_4). These two sets of four gages are arranged into two full Wheatstone bridges. The measurements are processed so as to obtain axial strain (weight), torsional strain (torque), and bending strain (bending). Processing of the weight, torque, and bending measurements uses the corresponding strain data from each of the three gage pockets and includes the compensation of the strain measurements for pressure and temperature. The measurement tool is made from non-magnetic, austenitic steel with minimum yield strength of 896.31 Mpa (130 ksi). The measurement tool is rated to 172.37 MPa (25 ksi) maximum operating pressure at 175ºC.

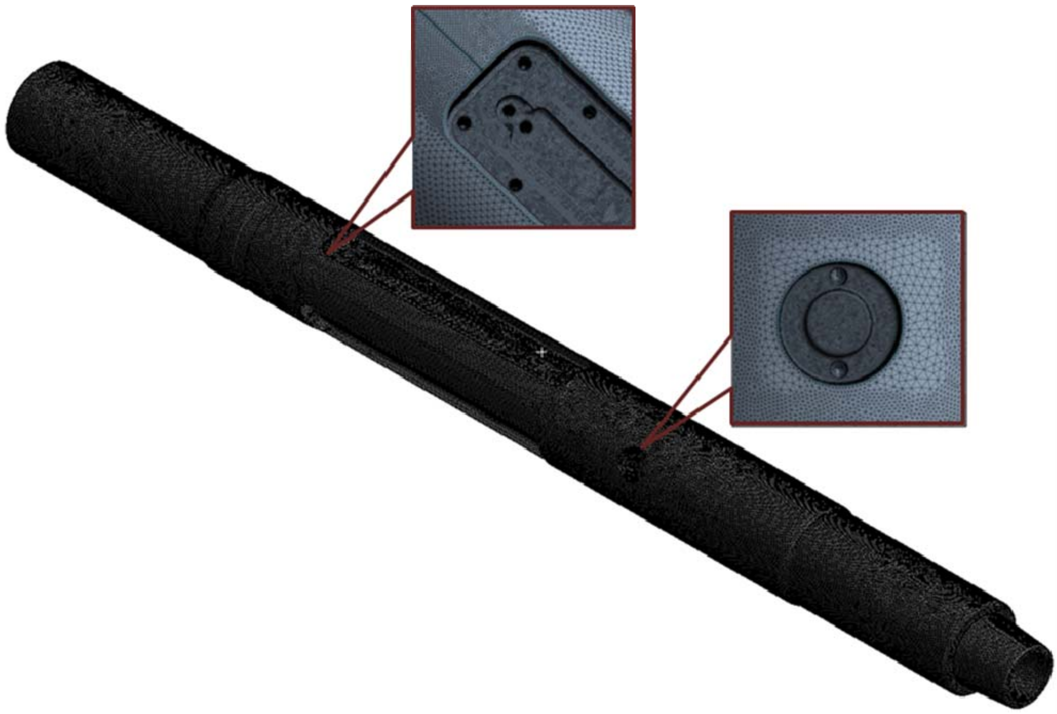

Fig. 2 Mesh Details

The 3-D finite-element analysis of the measurement tool subjected to known values of tension, compression, and bending moment is performed. In this analysis, a physical model of the tool is built using computer-aided modeling software. FEA numerical software is used to record the strain values at the eight strain-gage locations in each pocket. This experimentally proven FEA model is used for investigation of the strain, stress, and deformation pattern of combined loading conditions, which reflect the actual drilling environment.

After making the geometric model, the high-temperature mechanical properties are defined. The next step is to mesh the model in which the solid model is divided into nodes and elements. For this problem, a solid element with a higher order 3-D, 10-node element is used. With solid modeling, the geometric shape of the model is described, and instructions are then given to the FEA numerical software to mesh the geometry with nodes and elements. Fig. 2 shows a typical finite-element mesh for the measurement tool; superfine mesh is used at the critical locations to capture the stresses correctly. The number of nodes and elements for this model are approximately 66, 42,112 and 42, 94,242, respectively.

For validation of the FEA model, boundary conditions similar to experimental setup are applied (i.e., pure tension, compression, torque, and bending moment). The measurement tool is further analyzed under the application of combined loading conditions (i.e., actual drilling environment). The applied bending moment for particular dog leg severity (DLS) (i.e., hole curvature is computed with the help of bottomhole assembly program MaxBHA™), which uses a generic algorithm based on Lubinski's equations [4]. The maximum rated torque for standard thread connection of the measurement tool is used to account for maximum induced stresses.

The actual extreme operating conditions can be summarized as follows:

- Case 1: Bending moment, torque, and pressure differential
- Case 2: Axial loading, bending moment, torque, and pressure differential
- Case 3: Axial loading, bending moment, and internal and external operating pressure

Case 1 is the evaluation of the measurement tool for intense fatigue assessment. The bottomhole assembly is assumed to be rotating with motor up to 8°/30.48 m (8°/100 ft) dog leg severity (DLS). Because the tool is rotating, the maximum internal and external pressure differential is considered. In this case, WOB is ignored, as it will lower the working stress. Case 2 is the analysis of the measurement tool at the maximum tensile assumption of the bottomhole assembly. In this case, the measurement tool is being pulled by the bottomhole assembly from the bottom and is rotating with 14°/30.48 m (14°/100 ft) dog leg severity. Case 3 simulates the sliding of the measurement tool under a maximum 14°/30.48 m (14 deg/100 ft) dog leg severity. The BHA will not be rotating in this case; instead, the tool is being pushed through the curved hole. The extreme internal and external pressures have been considered to check bulk yielding of the tool.

III. Results and Discussion

The measurement tool was tested at the Halliburton testing laboratory with applied loading conditions of 200,170 N (45,000 lbf) compression, 200,170 N (45,000 lbf) tension, 29,421 N-m (21,700 ft-lbf) torque, and 40675 N-m (30000 ft-lbf) bending moment. The proposed FE model was further subjected to identical loading conditions, and strain measurements at particular locations were recorded. In Table I, FEA results are compared with experimental results, which show a close conformity between numerical and experimental results.

TABLE I
Comparison between Experimental and FEA Results

Nature of Loading	Experimental Loading	FEA Reading	% Error
Tension N (lbf)	200169.9 (45000)	200670.3 (45112.5)	1.7
Compression N (lbf)	200169.9 (45000)	200670.3 (45112.5)	1.7
Torque N-m (ft-lbf)	29421.3 (21700)	28667.4 (21144)	-2.6
Bending Moment N-m (ft-lbf)	40674.5 (30000)	38065.8 (28075.9)	-6.4

In addition to the result verification for a particular case, multiple cases of WOB and TOB conditions are analyzed to verify the accuracy of the FE model along the operating range of the measurement tool. The results obtained from the proposed FE models are compared with the experimental results, and good agreement is achieved, as shown in Fig. 3.

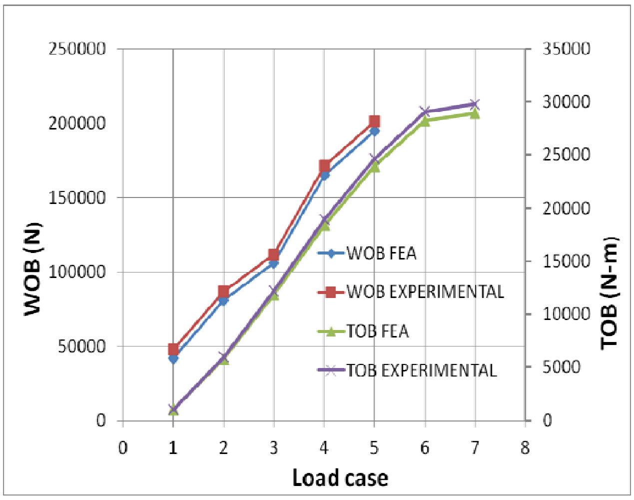

Fig. 3 Comparison between experimental and FEA results over operating range

TABLE II
FEA STRAIN VALUES UNDER COMBINED LOADING CONDITIONS

Strain Location	Strain × 10^{-6} (micro-strain)								
	Case 1			Case 2			Case 3		
	Pocket 1	Pocket 2	Pocket 3	Pocket 1	Pocket 2	Pocket 3	Pocket 1	Pocket 2	Pocket 3
W_1	249.31	248.88	-81.97	334.30	334.41	-351.53	-1531	-1533.8	-872.60
T_1	453.41	409.69	737.61	402.96	308.53	993.8	-777.77	-689.27	-1329.1
W_2	-175.45	-578.38	694.84	-232.88	-1069.5	1574.6	-198.61	588.41	-1897.4
T_2	-532.51	-568.66	-246.03	-587.23	-663.23	7.91	-772.78	-706.69	-1330.8
W_3	240.48	240.95	-77.66	322.35	322.57	-338	-1481.2	-1480.5	-844.47
T_3	418.95	451.52	737.16	324.88	396.73	990.2	-707.89	-771.78	-1327.9
W_4	-574.74	-172.59	696.15	-1065.1	-230.20	1573.9	584.43	-198.70	-1895.6
T_4	-575.37	-529.12	-242.14	-676.65	-580.3	15.68	-691.25	-776.71	-1335.0

To achieve a fatigue limit of 10^7 cycles under pure-reversed stress conditions, the strain limit is ± 2,000 micro-strain. To verify the maximum strain at the strain location, the proposed FE model is subjected to extreme loading conditions, and strain values are recorded at the different locations. From Table II, the maximum strain value under worst-case conditions does not exceed ±2,000 micro-strain, thus guarantees the strain-gauge cycles more than 10^7. The yielding criterion for the strain gauges is 14,000 micro-strains. From Table II, it can also be concluded that under extreme conditions, strain gauges can safely operate without structural damage, hence confirming gauge reliability.

The three combined load cases were analyzed to verify the magnitude of stress at critical locations and the stress distribution across the thickness of the measurement tool. As the dog leg severity (i.e., hole curvature) increases, the magnitude of bending moment increases, which, in turn, adds to the stress. The extent of applied pressure also has a significant impact on the value of stress as the amount of stored energy increases. In Case 3, the measurement tool is exposed to the operating pressure and maximum dog leg severity due to which the maximum stress value is more than other two cases.

The API design verification methods are based on linear-elastic stress analysis, with the maximum allowable stress limited to 83 to 90% of material yield strength [2]. Fig. 4 shows that the maximum von-Mises stress for Case 3 loading is 706 MPa (102.4 ksi), and the material has a specified stress limit of 896 MPa (130 ksi). The maximum allowable stress is more than the induced stress; hence, the measurement tool will successfully operate under the actual drilling environment.

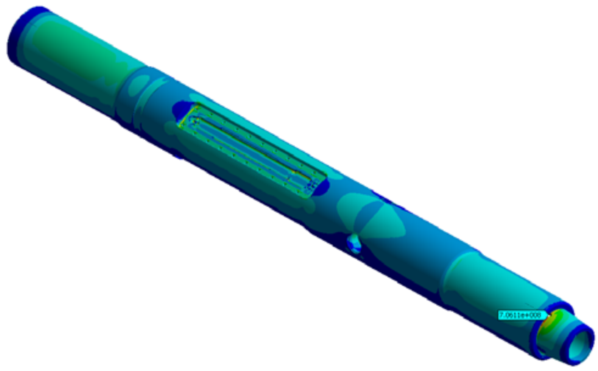

Fig. 4 von-Mises stress distribution for Case 3 loading

IV. CONCLUSION

The FE model is developed, tested, and implemented for the analysis of the stress/strain measurement tool under the tensile, bending, torque, and shear loads. This model facilitated the standardization of strain response under various combined loading conditions. The stress/strain measurement tool maintains structural integrity under actual operating conditions.

The stress and strain evaluated in this analysis can be used as inputs for fatigue analysis to determine the expected life of the measurement tool under the drilling environment.

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