MOHAMMED AHMED OMER B. ENG. (HONS) PETROLEUM ENGINEERING JANUARY 2012

Drillstring Vibration Analysis in Extended Reach Drilling (ERD) using WELLPLAN™

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by

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Dissertation submitted to the Geoscience & Petroleum Engineering Department
in partial fulfilment of the requirements
for the
Bachelor of Engineering (Hons)
(Petroleum Engineering)
JANUARY-2012

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CERTIFICATION OF APPROVAL

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Approved by,

____

Dr. Reza Ettehadi Osgouei

Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MOHAMMED AHMED OMER

Abstract

Oil and gas industry always aims efficient service with optimal expenses. This final year project, aiming to deal with one of the most important parameters, that has tremendous impact on drilling operations' time and cost. This parameter as mentioned above on the topic is a Drillstring Vibrations.

While drilling, Drillstring Vibration causes premature drillstring components and bit failure [8], and is a waste of drilling energy. To increase drilling efficiency, drillstring vibrations need to be monitored and analyzed and the optimum drilling parameters and practices need to be achieved as a well is being drilled. This results in a reduction in the drillstring failures and the amount of time spent tripping and/or fishing, and an increase in both bit life and drilling rate.

Drillstring dynamics is one of the most important limiting factors in extended reach drilling. This is because, long sections of the drillstring lie on the low side of the wellbore while rotating. When the rotary speed exceeds a critical threshold the drillstring starts to snake, sliding up and down the borehole wall [1]. If rotated further beyond the threshold speed, the drillstring will eventually start to whir which can cause severe damage to string components after only a short period of time [1]. Therefore, the main scope of the project, considering the earlier mentioned issues, a WELLPLAN software (Critical Speed Module) used. The project mainly dealt with drillstring, axial stress, bending stresses and torsional oscillations known as stick-slip motion of the bit.

Besides the WELLPLAN™ software, a matlab M.file was developed that uses some predetermined equations to estimate the critical drillstring vibrations, and critical operational speed taking into account the weight on bit, BHA length and rock compressive strength.

ACKNOWLEDGEMENT

First and foremost, I would like to thank the Almighty God for His blessings, and giving me health, strength and knowledge to complete this project.

My special and deepest gratitude and appreciation goes to my supervisor, Dr. Reza Ettehadi Osgouei for his help and limitless guidance throughout this work. Without his support and encouragement, this work would not have been completed.

I would like to express my gratitude to Mr. Azzumar Razali, Mr. Mohd Aimran, and Dr. Yasir Salih for their advice, support and help.

Lastly, I would like to thank all my family members, especially my parents for their love, encouragement, support and understanding throughout my study.

May Almightily God bless you all!!!

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CHAPTER 1:

PROJECT BACKGROUND

1.1 Introduction

This Final Year Project "**Drillstring Vibration Analysis''** tries to estimate the critical drillstring oscillation system and improve drilling operation by avoiding those critical rotation speeds (RPM). A background is given about the project in this chapter of the report followed by Literature review in chapter two. The third chapter explains project methodology and provides clear steps towards the success of the project. Chapter four provides the results obtained and discussion, while conclusion and recommendation presented in chapter five.

1.2 Problem Statement

1.2.1 Problem Identification

Vibration of drillstring has generated drilling operation problems, failure of drillstring components, such as RSS, MWD and LWD tools resulting in non-productive time. [6] What we see at the surface is not indicative of down hole in the subsurface. A potentially severe and complex pipe vibration takes place that leads to BHA failure, loss of energy and time [6]. Severe torsional drillstring vibrations can affect drill pipe and also bit life detrimentally. Empirically, these vibrations are associated with accelerated bit wear. These vibrations affect the Rate of Penetration (ROP) and can consume more frequently of the total time of classical rig time.

To be more specific we mention some of the main problems in point wise as bellow:-

- Premature BHA failure, especially MWD / LWD, and Rotary Steering Tools [6]
- Reduced ROP leads to waste of energy and time.
- Reduced Bit life

- poor result LWD logging quality due to hole condition

- Which in return the entire above four points combine to lead to unnecessary increased cost operation!

1.2.2 Significance of Project

The project is so significant for Oil and Gas Industry. The followings are some significant benefits of the project:

- Verify and predict critical drilling operation, by analyzing critical drillstring frequency and RPM.
- Reduction in tool fatigue and failure after determining those critical operations.
- Able to avoid cost through optimization of drilling operation.

1.3. Objectives and Scope of Study

1.3.1. Objective:

1) Analysis the stresses that contribute to drillstring vibration
2) Predict the critical and optimum string rotation (RPM) for the drilling operation
3) To determine the main factors that causes drillingstring vibration in ERD well.
4) Minimize BHA and bit failure, decrease energy consumption, decrease drilling operational time and cost.

1.3.2. Scopes of study:

The scope of the study revolves around the drillstring vibration analysis and critical rotary speed using WELLPLAN^{TM} and Matlab developed M.file. The nature of this study requires a thorough understanding of drillstring dynamics; the project tries to deal with a common problem in the Oil and Gas industry where one of the main concerns is tool fatigue and failure prevention. This program will assess and analyses stress on the drillstring and find the critical and optimum operation conditions. Besides that the main scope is:-

- Understanding pipe vibration properties
- Concise study on the RPM, WOB, and frequency excitation.
- Study and predict other factors that contribute to vibration.

1.4 Relevancy and Feasibility of the Project

The project believed to have valuable contribution and useful solution to Oil and Gas Industry. In fact, it improves drilling operations process. This project is relevant to Instrument and Control studies. The project had an adequate time frame to be completed even though few limitations were encountered. The area and scope of the project was also tolerable since the work that needs to be accomplished was achievable. Therefore, we can say that the project is feasible and of course completed within the allocated time frame.

CHAPTER 2:

Literature Review/Theory

2.1. How do we define Vibration?

Vibration in general is a motion of a particle or a body or a system of connected bodies displaced from a position of equilibrium and in most cases are undesirable [7].

2.2. Types of Vibration

Each and every physical substance vibrates at a natural frequency or rate of vibration. When the energy waves of different substances meet they excite each other and resonate, or increase. Drillstring, which is considered as connected pipe that end in a bit used to drill a well, can vibrate out of control and break when its resonance of harmonics achieved. The study of drilling system dynamics arose from a desire to improve drilling efficiency and protect expensive downhole components. These goals are achieved most readily through an integrated strategy comprising planning, real-time monitoring and detailed post-well analysis [1]. The planning phase begins with identification of dynamic dysfunctions most likely to occur during bit run. The most significant of these are vibrations which include:-[8]

(a) Axial-Bit bounce
(b) Lateral-Whirl
(c) Torsional-Stick slip
(d) Buckling or bending while rotating

2.3. Impact of Vibration on Drilling Operation

Any amount of drillstring dynamics is likely to have a negative impact on overall drilling efficiency. Under conditions of severe drillstring dynamics, all BHA components, from drill bits to MWD/LWD tools, rotary steerable systems, drill collars and drill pipe, are exposed to catastrophic failure that leads to time loss, downhole equipment loss, and even loss of hole section and direction. Managing drillstring dynamics through insight modeling and analysis is the crucial step in this project for preventing negative impact on drilling performance.

Drilling with high amplitude vibration results in accelerated drillstring fatigue, most current efforts aimed at understanding and controlling drillstring vibrations focus on the failure of drillstring components [12]. During drilling the drillstring transfers power from the surface to the bit, whereby, high amplitude drillstring vibrations formed, that may represent in loss or waste of drilling energy. Hence, high levels of vibration not only result in drillstring component failure but can also result in low drill rates.

2.4. Identifying Factors Contributing to Vibration

2.4.1. Main Factors

The main factors that have higher contribution to drillstring vibration and required for this project are;-

1- WOB, the weight on Bit
2- q, buoyant weight per unit length of the drillstring
3- EI, bending stiffness of the drillstring
4- u, vibrating mass per unit length
5- TOB, Torque on Bit
6- MW, Mad Weight
7- L, length of BHA, drill pipe, drill collars, and other drillstring assembly
8- r , radial clearance between drillstring and wellbore
9- Es, rock (formation) compressive strength
10- ρa, rock density and
11- Hs, Schmidt index

2.4.2. Inclination Angle

As inclination angle increases in directional, horizontal or inclined wells, the borehole walls support more of the drill string weight. This contact, along with the capstan effect (the normal force caused by the deformation of an axially loaded member about some obstacle), results in frictional forces that oppose the drill string's rotation and axial movement. During pipe rotation, frictional loading manifests itself as surface torque above and beyond that applied at the bit. During axial movement, it shows up as a difference in hook load between the indicated drill string weight and the actual vertical component of drill string weight, either as up drag (when pulling out of the hole) or down drag (when running in the hole). [3]

2.4.3. Dogleg Severity

Most commonly drillstring failure wear occurs in doglegs where the pipe goes through cyclic bending stresses. These stresses occur because the outer wall of the pipe in a dogleg is stretched and creates a greater tension load. As the pipe rotates a half cycle, the stresses change to the other side of the pipe. Fatigue damage from rotation in doglegs is a significant problem if the angle is greater than some critical value. [3]

2.5. Previous Researches

Dunayevski [4] determined the operating speed which causes parametric resonance to occur with unlimited growth in the magnitude of the vibration. In his second paper [5], Dunayovaki used the model to determine the effects of weight-on-bit, BHA length, drillstring length, and other operating parameters.

In 1985, Enertech Engineering and Research Company developed a simplified analysis of BHA vibrations based on harmonic analysis using finite elements. And the techniques were used to solve the harmonic equations, and the use of finite element allows the analysis to include coupled axial, torsional, and lateral vibrations. Data comparisons made with the model were encouraging, and the model was unique in its ability to identify critical operating speeds based on lateral vibration [9].

In 2000, Baker Hughes INTEQ GmbH [1] presented a paper on an analytical solution derived for the threshold rotary speed. The result was shown to be in the range of the rotary speeds used in modern extended reach applications. The analytical results were verified using a versatile finite element formulation to model the drillstring in greater detail. Animated time domain simulations model were provided to give deeper insight into the dynamic behaviour of the drillstring.

The main contribution of the paper was the derivation and determination of the minimum frequency for very long drill pipe sections. It is this equation used in this project to build the relation between the rotary speed (RPM) and weight on bit (WoB).

$$fmin = \frac{1}{2\pi}\sqrt{\frac{q}{ru} - \frac{F^2}{4EIu}} \text{ --------------------------------- (1)}$$

Where

F=WOB =Weight on Bit, (N)

f_{min}= minimum frequency, (Hz)

q =buoyant weight per unit length, (N/m)

EI=bending stiffness of the drillstring, (Nm^2)

u= vibrating mass per unit length, (Kg/m)

r = radial clearance between drillstring and wellbore, (m)

On another approach Dr. Bill Mitchell [2],in his Advanced Oil Well Drilling Engineering book 10th edition has coded "The longitudinal or torsional vibration frequencies of a tricone bit is usually found to be three times the rotary speed. It is thought that the bending and orbital motion of the BHA may in part be responsible for these vibrations." Based on that he developed several equations from which some of them used in this project.

From his work the equation for computing the critical rotary speeds for a BHA which is vibrating longitudinally, with a bit frequency equals the resonant frequency of the BHA, is as below:- [2]

$N_{crit\text{-}long} = N = 84240/L$

The natural frequencies and critical rotary speeds of the BHA without shock sub are given as follows:- [2]

$F_{long} = 4212/L$ -- (2)

$N_{crit\text{-}long} = N = 84240/L$-- (3)

$F_{tor} = 2662/L$--- (4)

$N_{crit\text{-}tor} = 53240/L$-- (5)

Where;

L= BHA (Drill Collar) lengh, (ft)

F_{long}, F_{tor}, longitudinal and tortional frequencies respectively, (Hz)

$N_{crit\text{-}long}$, $N_{crit\text{-}tor,}$ Critical longitudinal and tortional rotary speeds respectively, (RPM)

Note: - [2]

1. All of the above equations apply for vibrations without shock subs.

2. All match with tricone bits only.

3. First harmonic frequency is achieved (n=1)

4. Serious band widths of resonant frequencies are within the range of about $\pm$20 RPM

Energy balance of a drill-bit seismic source, part 1: Rotary energy and radiation properties

"The above article coded that the performance of a drill bit source is related to drilling power conditions. The total drilling power at the bit obtained by adding the torque power and the vertical work-per-unit time of the axial force (weight on bit or WOB). Where power is in kW": [10]

W_{drill} = (2πRPM × TOB)/60+ (ROP × WOB)/3600 -- (6)

Where;

W_{drill}=Drilling power, (KW)

RPM=rotary speed, (rev/min)

TOB=Torque on Bit, (KNm)

ROP=Rate of Penetration, (m/hr)

WOB=Weight on Bit, (KN)

The same article [10] has mentioned that the energy required by the bit to drill a rock, disregarding energy losses due to drillstring friction and damping presence due to drilling mud can be expressed as bellow. The article refers to (Rabia, 1985) for this concept.

E_S = (3600 × W_{drill}) /A × ROP--- (7)

Where;

Es = energy required at the bit to drill a unit rock volume and has the physical dimensions of stress

A = borehole area

Finally, besides the Wellplan software, all of the above equations are the main sources of our matlab M.file calculations.

2.6. Introduction to the software

Landmark is a Halliburton fully owned property and has been in existence since 1984 providing solutions to the Exploration and Production Industries' challenges through the continuous development and enhancement of leading high-science software and technology services. Landmark technologies help companies replace reserves by extending the life of mature fields and reducing the risks of developing smaller, deeper prospects.

The main classes that this software covers are WELLPLAN *(used in this project)*, Compass, Stress Check, Casing seat, and Well Cat [11].

This software is known by the trade mark WELLPLAN™ which is considered as a client-server engineering software system for drilling, completion, and well service operations.

WELLPLAN software is based on a database and data structure common to many of Landmark's drilling applications. This database is called the Engineer's Drilling Data Model™ (EDM™) and supports the different levels of data that are required to use the drilling software [11]. This is a significant advantage while using the software because of improved integration between drilling software products.

There are many modules under this software which includes, Torque Drag Analysis Module, Hydraulics Module, Surge Module, Well Control Analysis Module, Critical Speed Module (used in this project), Bottom Hole Assembly Module and Stuck Pipe Module [11].

2.6.1. Critical Speed Module

2.6.1a. Calculation Procedures for Critical Speed Analysis

The WELLPLAN Critical Speed program calculates resonant frequencies for a drill string rotating in wellbore as well as non-rotating steerable assemblies. The solution is obtained by first calculating the displaced static shape of the BHA in the wellbore. This means that the effects of hole angle, curvature, collar size, contact locations, and BHA displacement due to rotational friction effects can be modeled [11].

In carrying out the calculation of critical frequencies, or RPMs, the procedure is to solve a set of equations for a range of frequencies to determine the sensitivity of BHA displacement to the excitation frequency (e.g., 3X for tri-cone rock bits) [11]. The assumption is that at a critical frequency, or rotary speed, forced oscillations at the bit, stabilizers, or other contact points cause large displacements and stresses elsewhere in the drill string.

In addition, a mathematical formulation developed to admit damping in the steady-state response behavior [11].

2.6.1b. Imposed Load or Force Vector Excitation Calculation

The CSA solution is based upon an imposed load or force vector excitation *{P}*, and it is assumed the BHA is subjected to a harmonically varying form of the excitation *{P}* given by [11]:

$$\{P(t)\}= \{Ps)\} \sin wt + \{Pc\} \cos wt \text{ --- (Eq-n A)}$$

This yields a resulting steady state displacement response of

$$\{(u,t)\} = \{us\} \sin wt + \{uc\} \cos wt \text{-- (Eqn- B)}$$

The angular frequency (*w*) of the excitation is directly related to the rotary speed through the use of an excitation factor. The excitation factor designates how many times per revolution a given excitation occurs [11].

Substituting equations (A) and (B) into the Vibrational Analysis Equation, and implementing concepts from complex vector algebra, it is apparent that the steady state displacement field arising from the applied harmonic loading can be determined by solving for the solution of the linearized system of complex force-displacement relation given by [11]:

$$\{Pc\} + i\,\{Ps\} = ([J] - w^2\,[M] + iw[C])\,(\{uc\} + i\,\{us\}) \text{ --------------- (Eqn-C)}$$

Where:

$I = (-1)^{1/2}$

[J] = Jacobian matrix (contains the effects of contact, stress stiffening and friction)

[M] = Mass matrix

[C] = Damping matrix

During the vibration portion of the analysis, the CSA program will solve equation-C for a range of operating (RPM) speeds. At a critical rotary speed, small forced excitations at the point of application will cause large displacements and stresses elsewhere in the drill string [11].

2.6.1c. Input for FFR includes:

- Complete BHA/Drill String description
- Well information (i.e. wellpath data, hole size(s), and friction coefficient(s))
- Excitation loads and displacements, consisting of magnitude and phase angle
- Beginning and end of frequency range to be examined

2.6.1d. Analysis Techniques in CSA

Critical Speed (CSA) uses an engineering analysis technique called Forced Frequency Response (FFR) to solve for resonant frequencies (RPMs) [11]. All drill strings have natural axial, lateral, and torsional modes of vibration which can be "excited". This excitation may be in the form of displacements or contact forces at the bit, stabilizers, or along the string. One well known and documented excitation is due to the tri-cone drill bit rolling over high and low spots in the formation. This type of excitation produces axial and torsional bit displacements having frequencies of three cycles per revolution [11].

Another source of excitation can result from stabilizers rubbing against the wellbore. When stabilizers contact the wellbore, frictional forces develop as a result of the contact and rotation and can produce self-excited vibrations. This self-excitation will feed energy into the torsional vibration mode [11].

CHAPTER 3:

3.1. Methodology

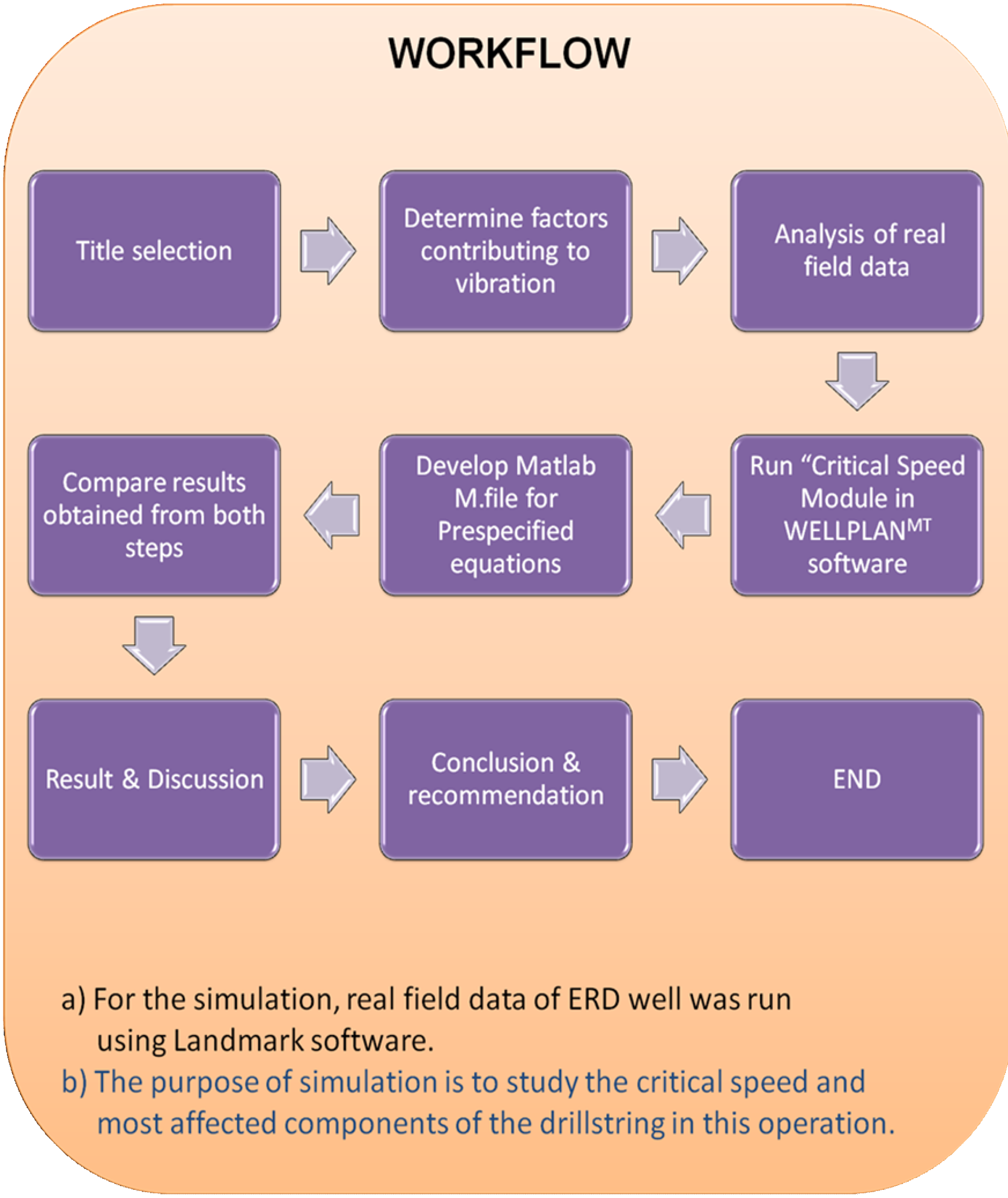


Fig.1 Workflow

3.2 Project Activities

The project activities comprises of two main phases, one in which the Landmark release 5000.1 WELLPLAN^{TM} "Critical Speed Module" used, the second phase is the calculation phase where a matlab M.file developed by implementing the predetermined equations.

3.2.1. Critical Speed Module Phase

As all of the engineering applications in WELLPLAN^{TM}, Critical Speed Analysis uses data specified for the Active Case [11]. Those data used are:-

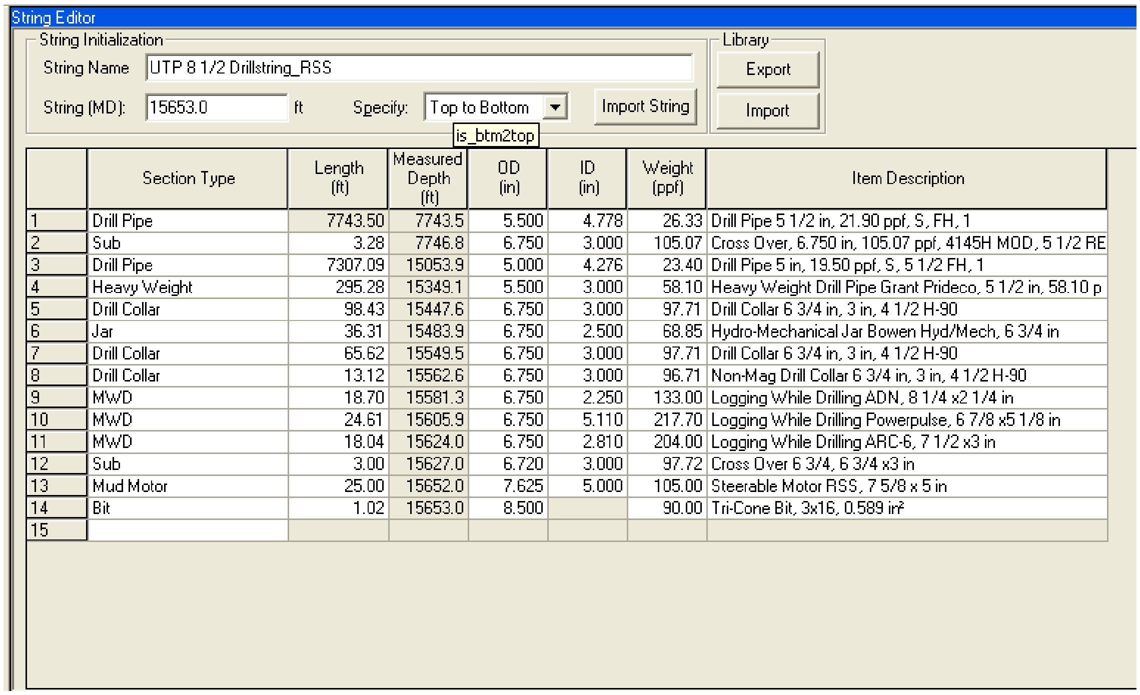
- Hole Section: MD (9842.5 -15653) ft
- Cased Section: - MD (0-574), (574-2952.5), (2952.5-9842.5) ft
- Fluid: - 10.5 ppg
- ROP = 15 m/hr
- WOB = 25Kips = $1.11*10^5$ N
- Drill String: - Detailed in the figure below (obtained from field data) and
- Wellpath

General Procedures [11]

1. On the WELLPLAN window, File > Well was selected.
2. The Well for which we need to determine the critical speed was created.
3. Using the editors available on the Case menu on the WELLPLAN window, the physical characteristics of the well were described. (Data requirements for Critical Speed were specified previously.)
4. On the WELLPLAN window, Modules > Critical Speed Analysis was selected.

5. Select Parameter > Analysis Parameters. Parameters into the Critical Speed Analysis Parameters dialog were input, and then clicked the OK button.
6. Select Parameter > Boundary Conditions. Input the boundary conditions into the Boundary Condition Options dialog, and then clicked the OK button.
7. Finally, the plots needed were selected from the View menu.

   Note:- All the data used were provided from field data



	Section Type	Length (ft)	Measured Depth (ft)	OD (in)	ID (in)	Weight (ppf)	Item Description
1	Drill Pipe	7743.50	7743.5	5.500	4.778	26.33	Drill Pipe 5 1/2 in, 21.90 ppf, S, FH, 1
2	Sub	3.28	7746.8	6.750	3.000	105.07	Cross Over, 6.750 in, 105.07 ppf, 4145H MOD, 5 1/2 RE
3	Drill Pipe	7307.09	15053.9	5.000	4.276	23.40	Drill Pipe 5 in, 19.50 ppf, S, 5 1/2 FH, 1
4	Heavy Weight	295.28	15349.1	5.500	3.000	58.10	Heavy Weight Drill Pipe Grant Prideco, 5 1/2 in, 58.10 p
5	Drill Collar	98.43	15447.6	6.750	3.000	97.71	Drill Collar 6 3/4 in, 3 in, 4 1/2 H-90
6	Jar	36.31	15483.9	6.750	2.500	68.85	Hydro-Mechanical Jar Bowen Hyd/Mech, 6 3/4 in
7	Drill Collar	65.62	15549.5	6.750	3.000	97.71	Drill Collar 6 3/4 in, 3 in, 4 1/2 H-90
8	Drill Collar	13.12	15562.6	6.750	3.000	96.71	Non-Mag Drill Collar 6 3/4 in, 3 in, 4 1/2 H-90
9	MWD	18.70	15581.3	6.750	2.250	133.00	Logging While Drilling ADN, 8 1/4 x2 1/4 in
10	MWD	24.61	15605.9	6.750	5.110	217.70	Logging While Drilling Powerpulse, 6 7/8 x5 1/8 in
11	MWD	18.04	15624.0	6.750	2.810	204.00	Logging While Drilling ARC-6, 7 1/2 x3 in
12	Sub	3.00	15627.0	6.720	3.000	97.72	Cross Over 6 3/4, 6 3/4 x3 in
13	Mud Motor	25.00	15652.0	7.625	5.000	105.00	Steerable Motor RSS, 7 5/8 x 5 in
14	Bit	1.02	15653.0	8.500		90.00	Tri-Cone Bit, 3x16, 0.589 in²
15							

Fig.2 Drillstring Tally

3.2. 2. Calculation Phase

In this phase calculations aided by matlab were used. The equations mentioned in the literature review and some more are the main calculation tools for this phase. To fit our needs some modifications are carried out in some of the equations without altering their original bases.

Equations Modifications:-

1. Combining equation (2) and (3) we can draw the relationship between frequency and rotary speed, i.e.

$$f= 0.05\ N \text{ --- } (8)$$

2. Combining equation (1) and (8) results in;

$$N= 10/pi*[(q/ru) - (WoB^2 /4EIu)]^{0.5} \text{ --- } (9)$$

3. Combining equation (6) and (7) results in;

$$RPM= (Es*A-WOB)*ROP/ (120*pi*TOB) \text{ --- } (10)$$

4. According to the previous mentioned article [10], Pessier and Fear (1992) pointed out that the minimum (optimal) specific energy is reached when Es is roughly equal to the compressive strength σ of the rock being drilled, which is defined as the strength at which rock failure occur.

To compile equation (10) some more relations are required to calculate the compressive strength of rock which is assumed to be the optimal specific energy (Es) as pointed out by Pessier and Fear (1992) [10]. Comparing rebound values to laboratory determined compressive strengths and elastic moduli, Aufmuth [13] found a better correlation obtained by multiplying the rebound index by rock density.

$$\sigma a = 6.9*10^{[1.348\log(Hs*\rho a)-1.325]} \text{ --- } (11)$$

$$Et=6.9*10^{[1.861+1.061\log (Hs*\rho a)]} \text{ --- } (12)$$

Where;

σa = Compressive strength of rock, MPa

Et= Young Modulus of elasticity, MPa

ρa=Rock density, g/cm3

Hs= average rebound index

The above equations describe the best-fit approximations relating compressive strength and elastic modulus to the Schmidt hammer index [13]:

5. In this study the below five different rock types tested for RPM versus their specific energy as they are believed to be the most common formations in most fields.

Rock type	Young's Modulus 104 MPa(MN/m2)	Density (g/cm3)
Granite	2.55-6.89	2.65
Dolomite	1.93-8.2	2.86
Limestone	0.965-7.86	2.71
Sandstone	0.483-8.41	2.40
Shale	0.758-2.69	2.75

rock types

3.3. Gantt Chart

Timelines for FYP 1

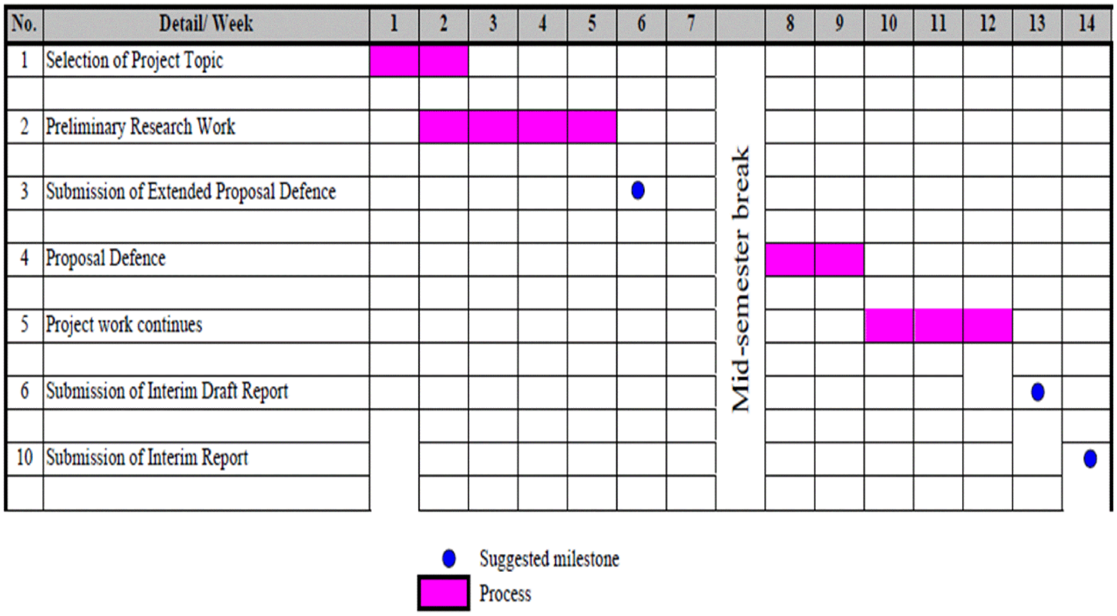


Fig.3 FYP 1 Timeline

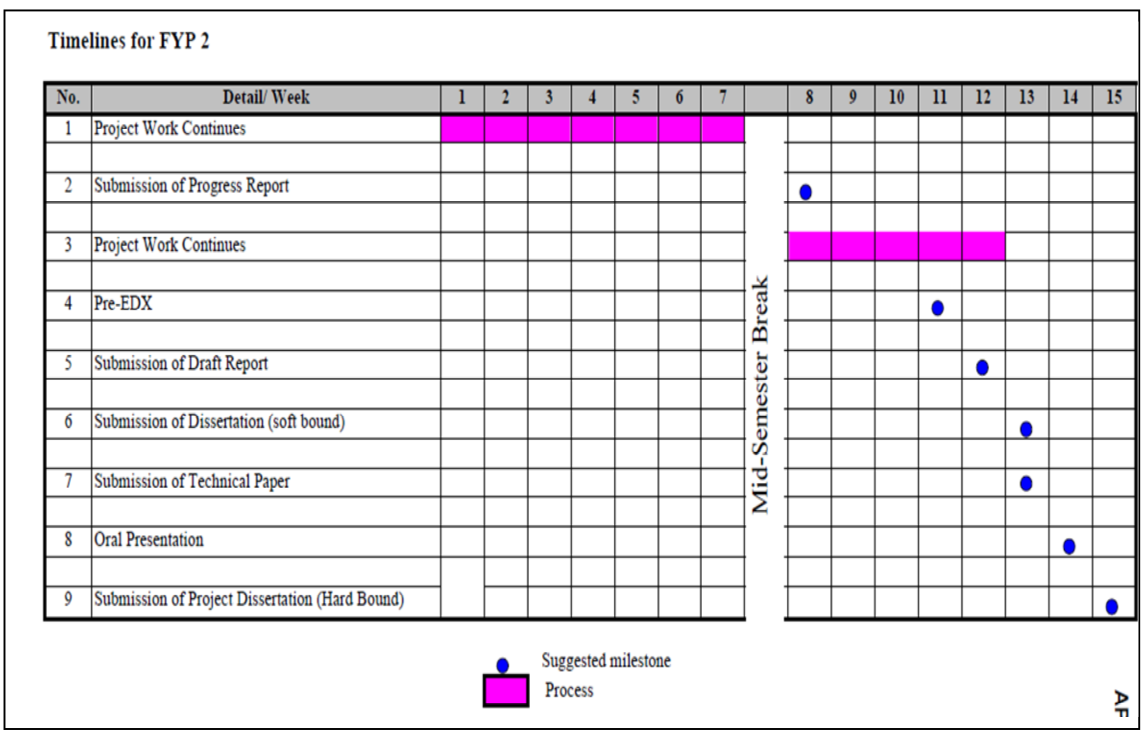


Fig.4 FYP 2 Timeline

CHAPTER 4:

RESULTS AND DISCUSSION

4.1. Critical Speed Module (WELLPLAN)

To run the critical speed analysis module, the data in section 3.2.1 and fig.2 drillstring tally were used. And the following results obtained. All results of discussion in this chapter focuses on the main hole section.

4.1.1. Rotational Speed Plots vs Resultant Stresses

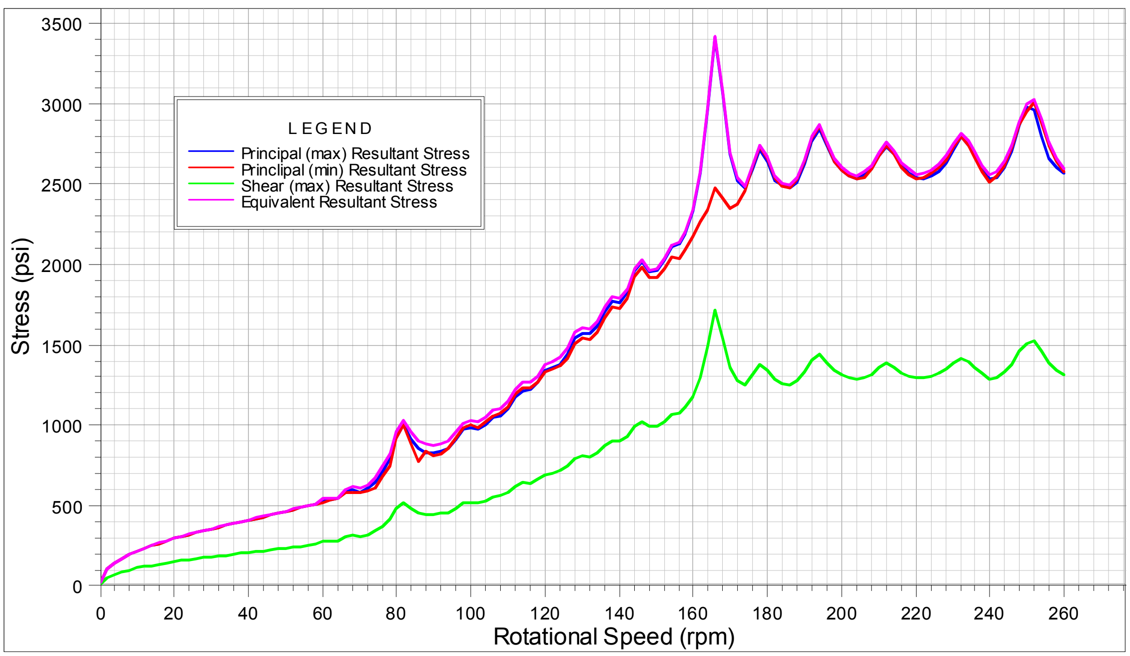


Fig5. Rotational Speed vs Maximum Relative Resultant Stresses

The above graph plots the maximum relative stress at different points in the drillstring against the rotational speeds (RPM). "These stress numbers are relative stress and not actual stress [11]. They represent stresses above and beyond steady state stresses that are caused by vibrations. They are relative to the magnitude of the forcing function used and, thus, used only for locating critical (or dangerous) rotating speeds."[11].

Hence the most critical spots in this operation are found to be at RPM equals to 82 and 166. Depending on this simulation, drilling operation at 160 and above is not recommended. Because of the higher and fluctuating occurrence of stresses on the drillstring might result in catastrophic drillstring failure.

Generally, drilling operating at RPM< 70 and 90<RPM<160 should be acceptable as per the above graph results. However, the positions of these pick spots in the drillstring and the affected components of the string will be showed and discussed in brief on coming graphs.

The plotted resultant stresses are [11]

- **Principal (max) Stress**– it refers to the maximum normal axial stress, occurring on the principal plane and perpendicular to the principal (min) stress. On the principal plane, the shear stress equals zero when the axial stress is a maximum.
- **Principal (min) Stress** – The minimum normal axial stress, occurring on the principal plane, and perpendicular to the principal (max) stress. On the principal plane, the shear stress equals zero when the axial stress is a minimum.
- **Shear Stress** – stress created in opposite directions parallel to the plane of contact when the drillstring and another contacting part slide upon each other.
- **Equivalent Stress** – the maximum relative equivalent stress is the maximum combined stress, summing up the principal (max) stress plus the principal (min) stress plus the shear stress

4.1.2. Rotational Speed Plots vs Stress Components

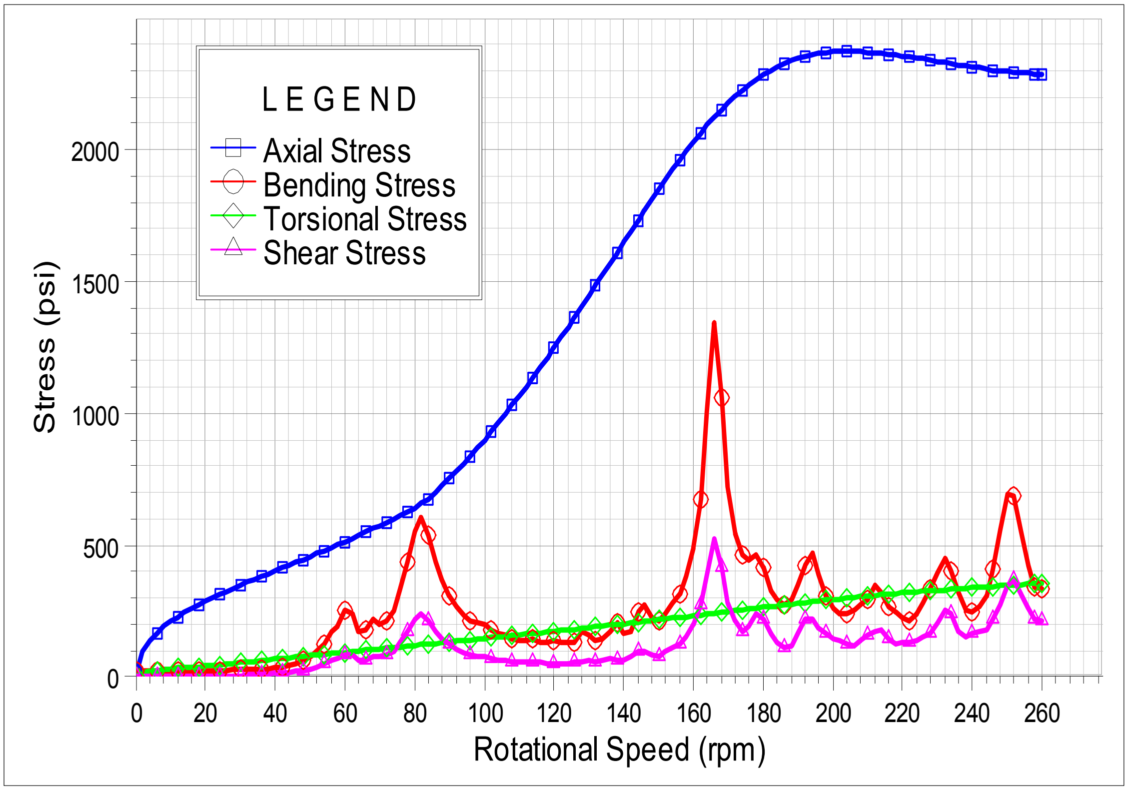


Fig.6. Maximum Relative Component Stress vs Rotational Speed

This graph plots the maximum relative value of each of the four stress components at any point in the drillstring versus RPM [11]. In this operation, the most critical pick spots were found to be at RPM equals 166 and 250 with 82 relatively moderate.

Axial Stress –The simulation proves that not necessary for the drillstring to be straight, still bit bounce can be a severe axial stress. Above 80 RPM the axial stress increases with steeper slop till it reaches 180 RPM.

Bending Stress – transverse stress created by tension at the bottom surface pushing against compression at the bit [11], resulting in bending or bowing of the drillstring at these pick spots. Mainly Axial and Bending stresses are the main concern in this operation.

Torsional Stress– Stress created by rotational oscillation of the drillstring, resulting in twisting and turning motion occurring in multiple dimensions, modeling a classic wave formation. And it increased almost with a direct proportionality with the increase of RPM in this operation.

Shear Stress – stress created in opposite directions parallel to the plane of contact (formation) when the drillstring and another contacting part slides upon each other.

4.1.3. Relative Magnitude Component Stress vs Distance from Bit at critical RPMs

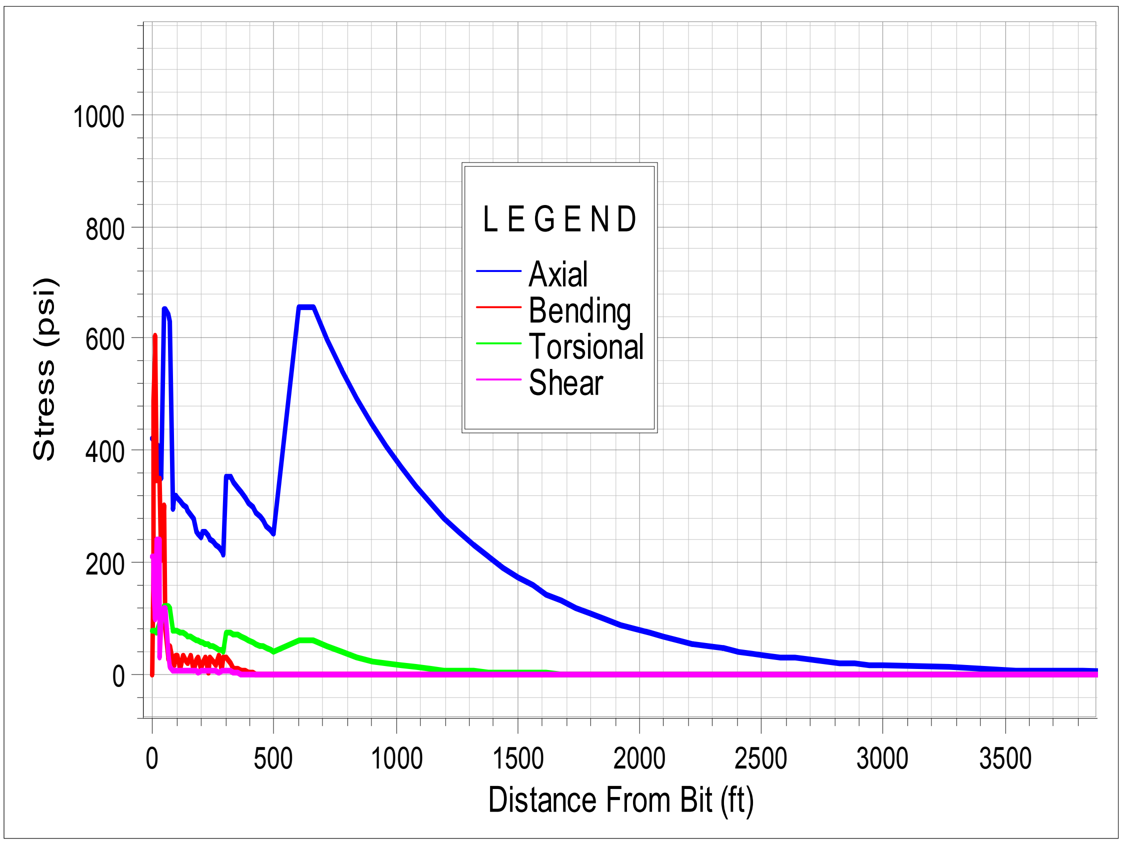


Fig.7 Relative Magnitude Component Stress vs Distance from Bit at 82 RPM

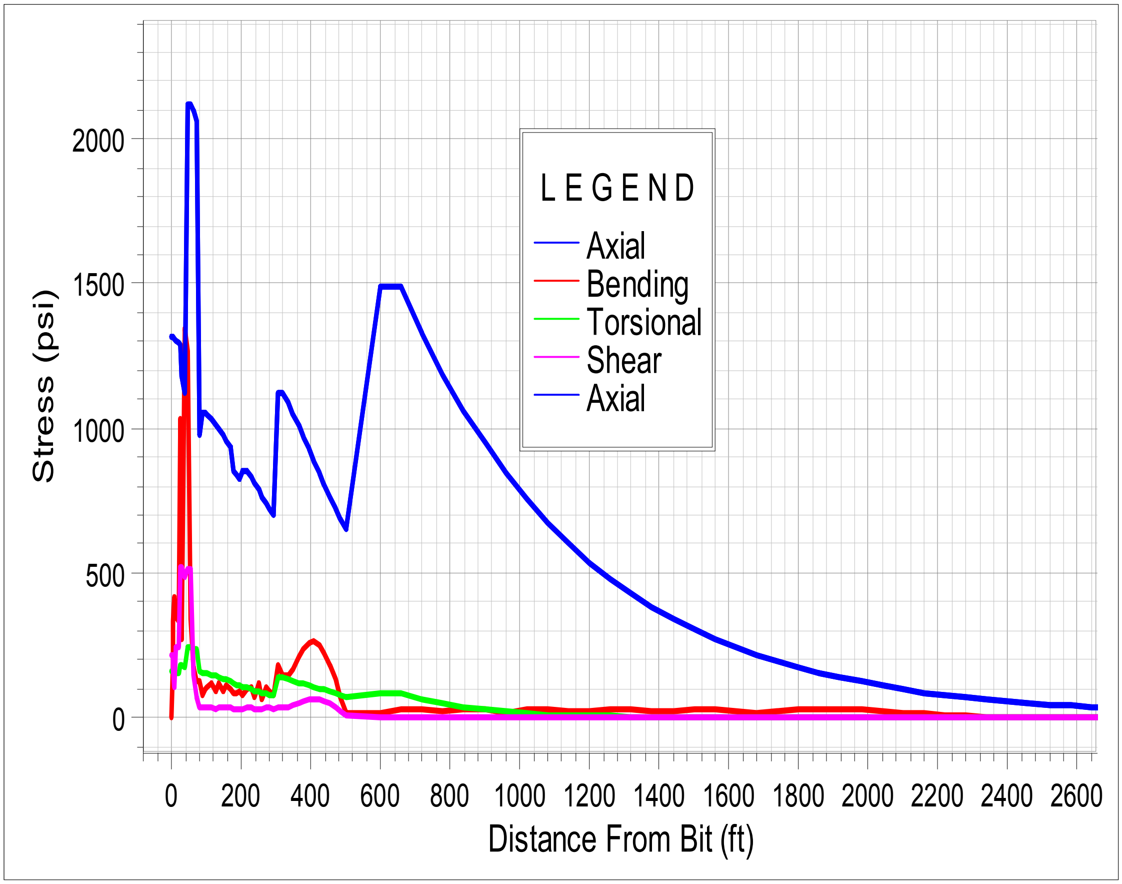


Fig8.Relative Magnitude Component Stress vs Distance from Bit at 166 RPM

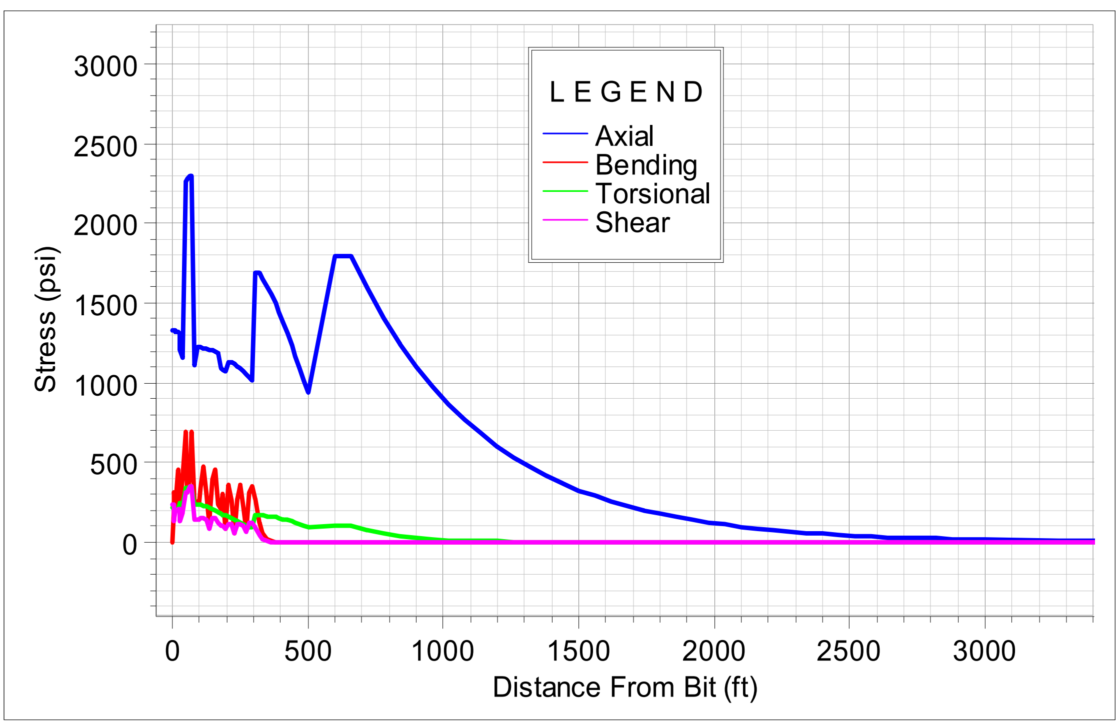
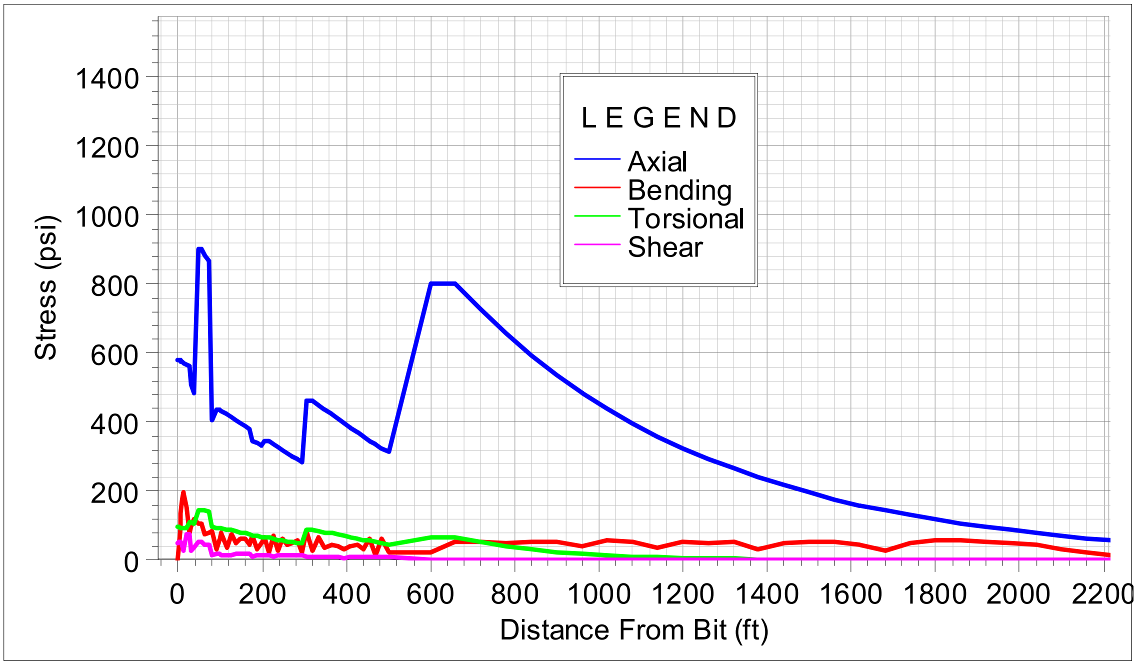


Fig9.Relative Magnitude Component Stress vs Distance from Bit at 250 RPM

- Figures 7, 8 and 9 selected as the most critical operation.
- At 166 and 250 RPMs high Axial and Bending stresses encountered during the drilling at a distance of about 19 to 47 ft from the bit.
- The most affected string components are the RSS and MWD.
- Again at distances about 600-660 ft from the bit high axial strength has encountered, this mainly at part of the drill pipe.
- Those drillstring components have less axial resistance compared to the rest of the string.
- As recommendation, they might need to be replaced with more high quality materials (grade) that can stand axial forces and stresses, to avoid unnecessary failure.
- To reduce the high axial stresses, the use of shock absorber sub might be a wise idea.
- At RPM equal to 82 and 166 higher bending stress has appeared, which is not at 250 RPM. At these RPMs the RSS and MWD tools encountered higher bending stress.
- The simulation on the critical speed module has showed that the optimum RPM depending on this operation is between 100-130 RPM, as in the fig.10 and 11.
- In this range of RPM all the bending, torsional and shear stresses are at their lowest pick, while axial stress is relatively high compared to the rest.
- This is mainly because of high axial force exerted with the increasing rotary speeds.
- Components with high grade might be used to overcome the high axial stress.

4.1.4. Relative Magnitude Component Stress vs Distance from Bit at optimum RPMs



10. Relative Magnitude Component Stress vs Distance from Bit at 100 RPM

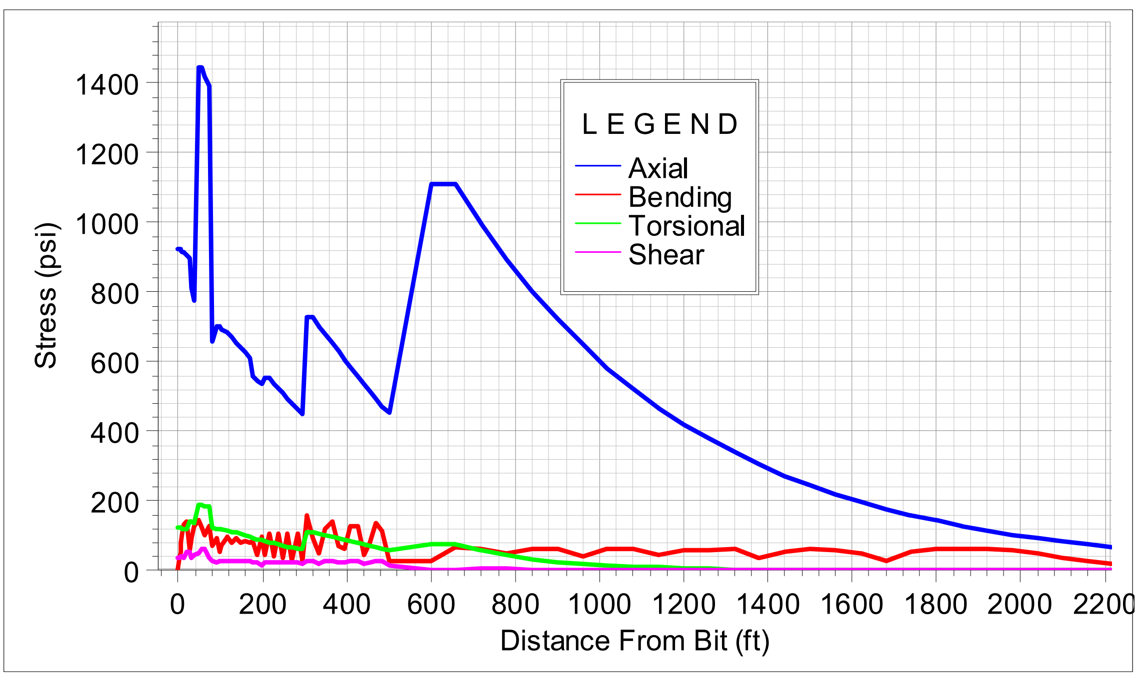


Fig11. Relative Magnitude Component Stress vs Distance from Bit at 130 RPM

4.2. Matlab Calculations Results

Using the equations and assumptions mentioned earlier the following out comes have been achieved.

4.2.1. Method one

Method one uses the relation between the rotary speeds (RPM) and Drill collar (BHA) length. Referring to Dr. Bill Mitchell's Advanced Oil well drilling engineering book, calculation was carried out depending on the BHA length. Hence, the shaded regions were found as critical operation zones. The below graph showed that the RPM is inversely proportional to the BHA length. That is to say, as BHA length increases the critical RPM reached at lower RPMs. This leads to the conclusion that, long BHA resonance frequencies occur with just small excitation.

In this study the BHA is almost 600 ft, therefore, the recommended operation ranges between RPM<68.7, 109<RPM<120, RPM>160. (See fig.12)

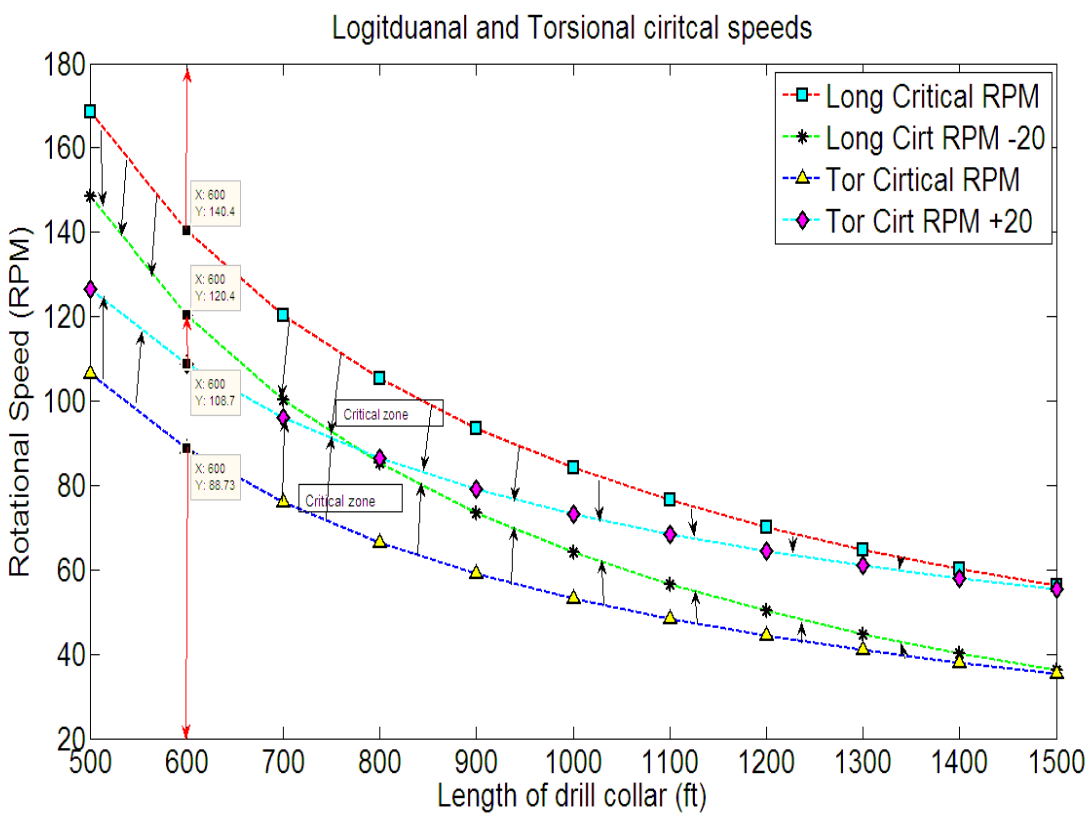


Fig12. Critical Longitudinal and Torsional Speeds vs L_{dc}

4.2.2. Method Two

In method two, relations between rotary speed (RPM) and the specific energy required to drill a unit volume of rock (Es) was used. Here, equation (10) and (12) were used in matlab, rotary speeds for five types of rocks were determined depending on their respective compressive strength as per assumptions at the methodology. Since the compressive strength corresponds to the minimum energy required by the bit to drill a unit volume of rock, then the rotary speeds found from this method absolutely represents the optimal drilling operation.

The conclusion from this method is that, RPMs less than 117 is quite enough to drill any of the chosen rock samples. Therefore, the range of operation to drill in most formations depending on their specific energy is roughly 30-120 RPM. (See fig.13)

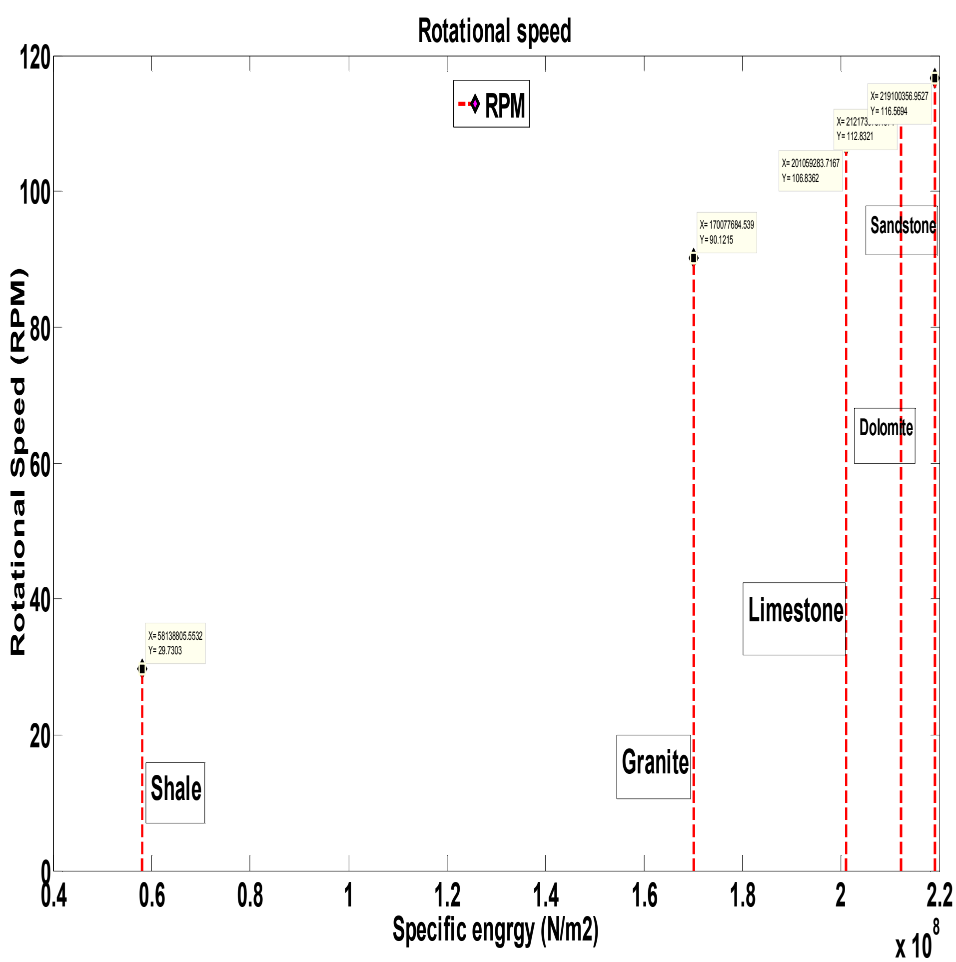


Fig.13 Rotational Speed vs Es

4.2.3. Method Three

In part three relations between rotary speed (RPM) and weight on Bit (WoB) were conducted using matlab. Implementing equation (9), the following results were obtained. The relation shows that the RPM tends towards zero with very high WoB. A minimum RPM of 62 were recorded for this study in which a $1.11*10^5$ N WoB was obtained from the field data. (See fig.14)

All matlab calculations are provided in the appendix of this report.

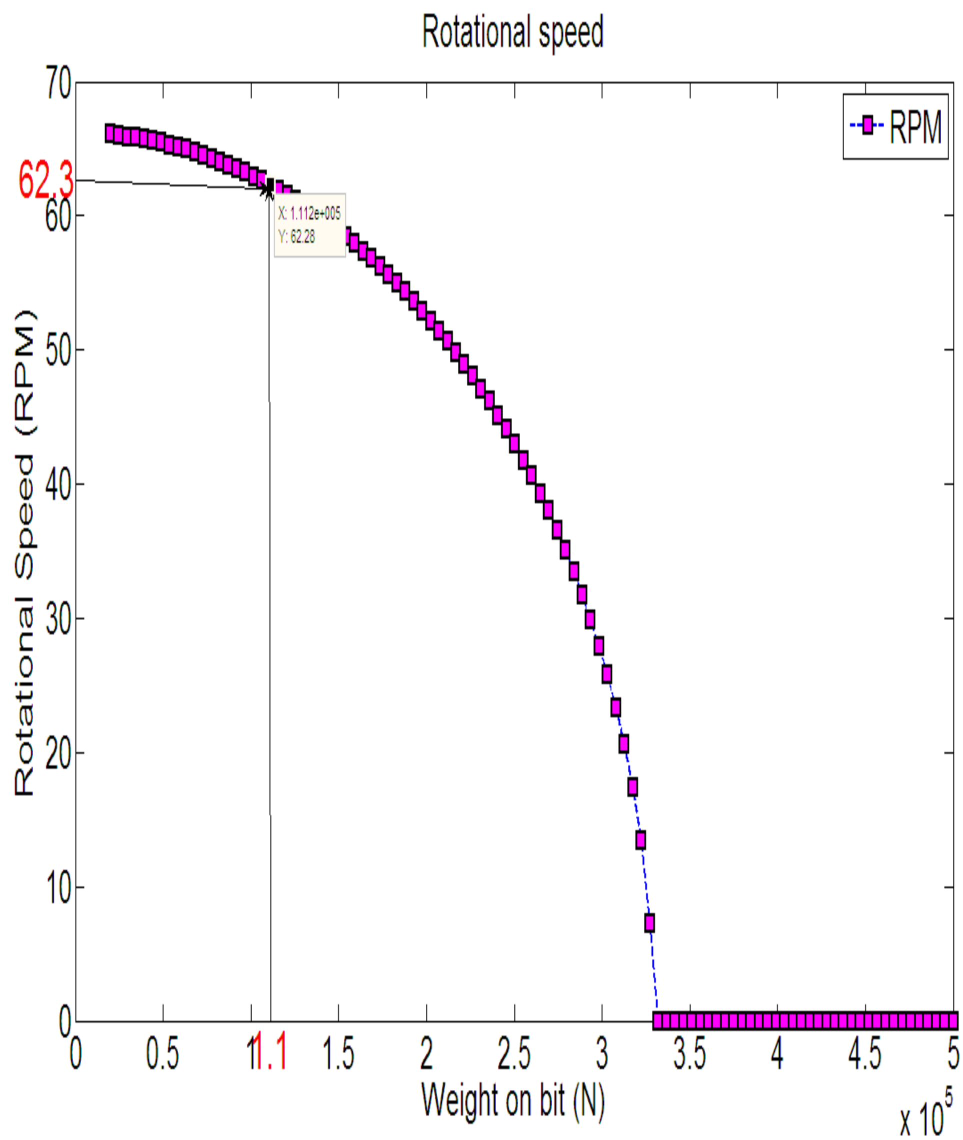


Fig.14. Rotational Speed vs WoB

4.3. Summary of Results

Depending on the software and matlab results the following overall results can be concluded.

Methods	Safe Operation Range
Matlab method 1	RPM<68.7, 109<RPM<120, RPM>160,
Matlab method 2	30<RPM<120 (Optimum)
Matlab method 3	RPM = 62.3 (minimum)
Critical Speed Module (WELLPLAN™)	RPM<80, 90<RPM<155 (fig.5)
Overall optimum operation	100-140 RPM

CHAPTER 4:

4.1. Conclusion

Method one has represented the critical RPM in a wide range and has shown the relation between RPM and BHA length with high realistic results. Method two has focused on rotary speed in correspondence to rock specific energy and has showed equivalent result to the software model. Generally, both methods have presented a very close results to the one obtained using the software. And most of the results obtained by the methods discussed lies within the software model range.

Therefore, in regions where Landmark not accessible or not available at all as at rig sites, the combination of these methods can be used with high confidence. Specially when a pre-developed m.file or excel macro is available. All in all, we can say the methods have shown confident results, even though the software still reserves the upper hand over them. This is because of the assumptions used in the methods by the authors as well as by this study.

Finally, depending on the overall results obtained we conclude that the optimum drilling operation lies within the range of 100-140 RPM for this study.

4.2. Recommendation

Now days many researches are carried out on drillstring vibrations, but most of them have come up with proposals of expensive software. Hence, we strongly recommend a comprehensive further study on these methods for their development and validations. The methods should be developed to include more factors that believed to affect the vibration of the drillstring. With concise study I believe these methods can be widely used in the oil and gas industry for their simplicity and time saving.

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Appendices

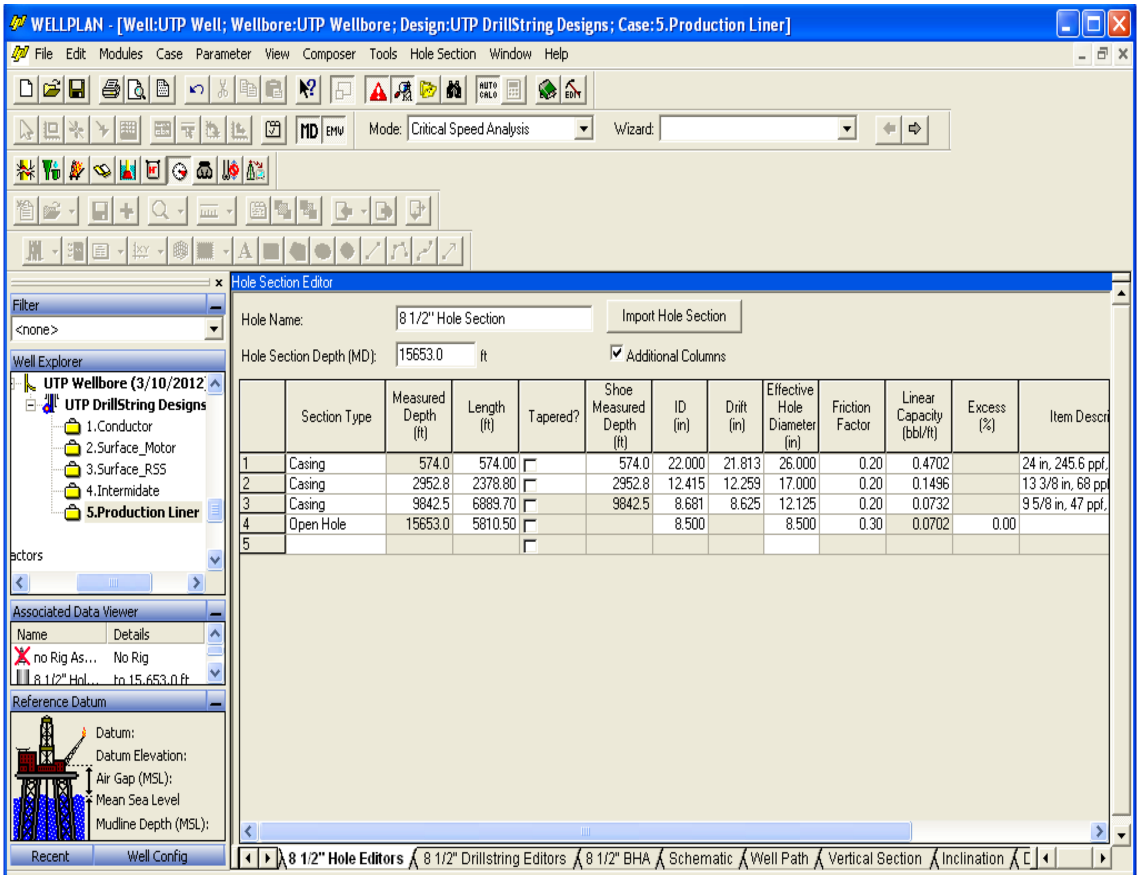
Appendix A

Matlab coding

```
%% Mohammed Ahmed Omer      PE      12919

%% Part 1
% Length of drill collar
Ldc = 500:100:1500;
%% Output one
% RPM when logitduanal vibraiotn
RPM_LongCir = 84240./Ldc;
RPM_mins20 = 84240./Ldc - 20;
% Tortional ciritcal
RPM_TorCir = 53240./Ldc;
RPM_pls20 = 53240./Ldc + 20;
figure(1);
% plot the ciritcal rpm
plot(Ldc, RPM_LongCir,'--rs','LineWidth',2, 'MarkerEdgeColor','k',...
                'MarkerFaceColor','c','MarkerSize',10);
% hold on to draw second graph with the first one
hold on;
% plot second graph RPM - 20
plot(Ldc, RPM_mins20, '--g*','LineWidth',2, 'MarkerEdgeColor','k',...
                'MarkerFaceColor','m','MarkerSize',10);
% plot thrid graph RPM Tor cirtical
plot(Ldc, RPM_TorCir, '--b^','LineWidth',2, 'MarkerEdgeColor','k',...
                'MarkerFaceColor','y','MarkerSize',10);
% plot forth graph RPM + 20
plot(Ldc, RPM_pls20, '--cd','LineWidth',2, 'MarkerEdgeColor','k',...
                'MarkerFaceColor','m','MarkerSize',10);
% stop the hold on
hold off
% make title for the figure, lengend for the graphs and label the axis
title('Logitduanal and Torsional ciritcal speeds');
legend('Long Critical RPM', 'Long Cirt RPM -20', 'Tor Cirtical RPM',
'Tor Cirt RPM +20');
xlabel('Length of drill collar (ft)');
ylabel('Rotational Speed (RPM)');

%% Part 2
% Young modulus
% Rocks Types
Rocks = {'Granite', 'Dolomite', 'Limestone', 'Sandstone', 'Shale'};
E = [6.89e4, 8.2e4, 7.86e4, 8.41e4, 2.96e4];
% Density
RockDensity = [2.65, 2.86, 2.71, 2.4, 2.75];
% Rate of penteratoin
RoP = 15;
% hole diameter
D = 8.5/39.37;
% hole area
```

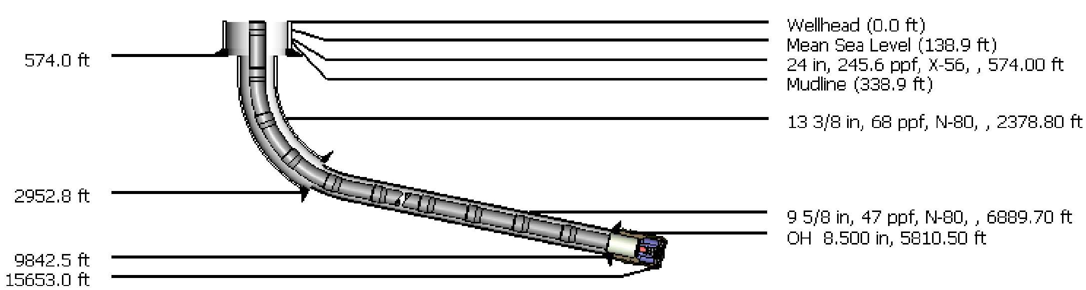
```
A = pi*D^2/4;
% Torque on bit
ToB = 2.7e3;
% Weight on bit
WoB = 111e3;
% Schimtd Hummer Index
Hs = 10.^((log10(E/6.9) - 1.861)/1.061 - log10(RockDensity));
% Specific engergy range
Es = 6.9*10.^(1.348*log10(Hs.*RockDensity) - 1.325)*1e6;
% Rotational Speed
RPM = (RoP)*(Es*A - WoB)/(120*pi*ToB);
figure(2);
% plot the ciritcal rpm
stem(Es, RPM,'--rd','LineWidth',2, 'MarkerEdgeColor','k',...
                'MarkerFaceColor','m','MarkerSize',10);
% make title for the figure, lengend for the graphs and label the axis
title('Rotational speed');
legend('RPM');
xlabel('Specific engrgy (N/m2)');
ylabel('Rotational Speed (RPM)');

%% Part 3
% WoB range
WoB = 2e4:(5e5-2e4)/100:5e5;
% hole diameter
Dh = 8.5;
% Drill collar dimater
Ddc = 6.75;
% clearance radius
r = (Dh - Ddc)/2*(1/39.37);
% mass per length
u = 37.1;
% pipe stiffness
Ei = 1.69e6;
% Buoyant weight
q = 356.3;
RPM = 10/pi*sqrt(q/(r*u) - WoB.^2/(4*Ei*u));
figure(3);
% plot the ciritcal rpm
plot(WoB, RPM,'--bs','LineWidth',2, 'MarkerEdgeColor','k',...
                'MarkerFaceColor','m','MarkerSize',10);
% make title for the figure, lengend for the graphs and label the axis
title('Rotational speed');
legend('RPM');
xlabel('Weight on bit (N)');
ylabel('Rotational Speed (RPM)');
```

Appendix B



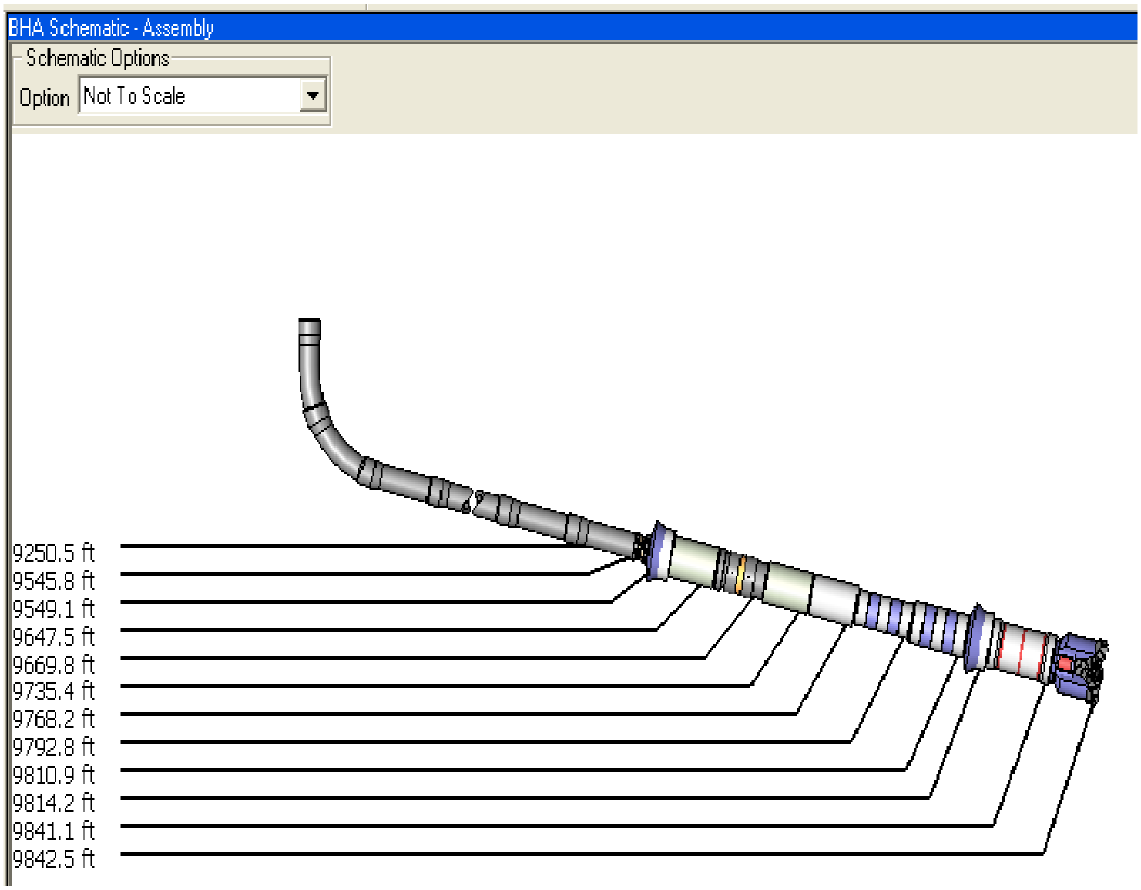
Casing and open hole section editor (8 1/2") section

Appendix C



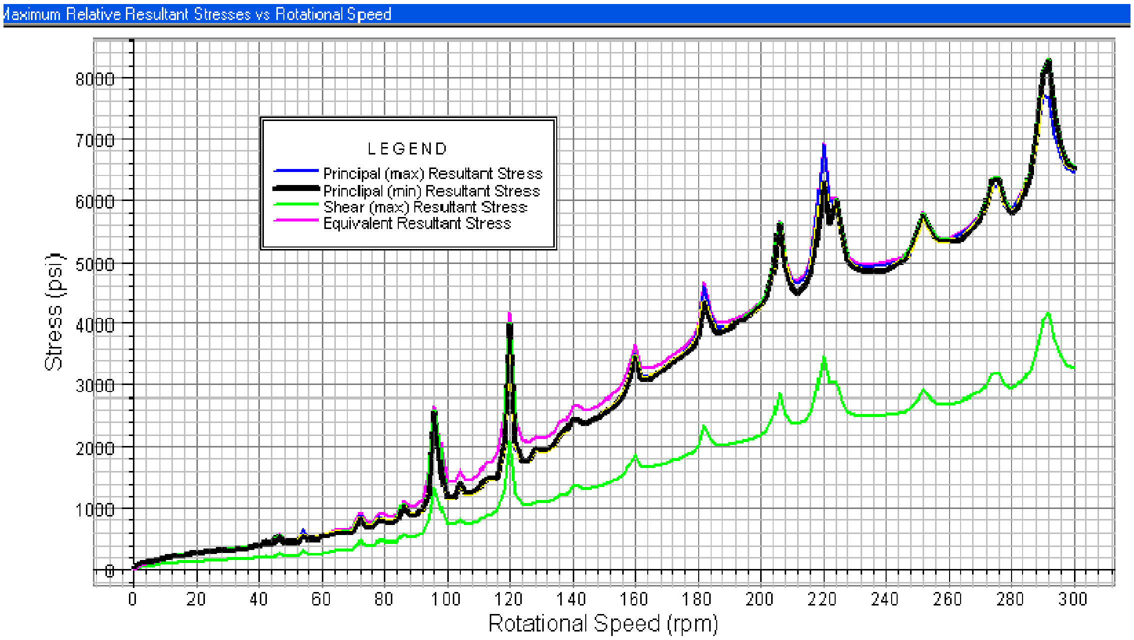
Well – Full String Schematic (8 1/2") section

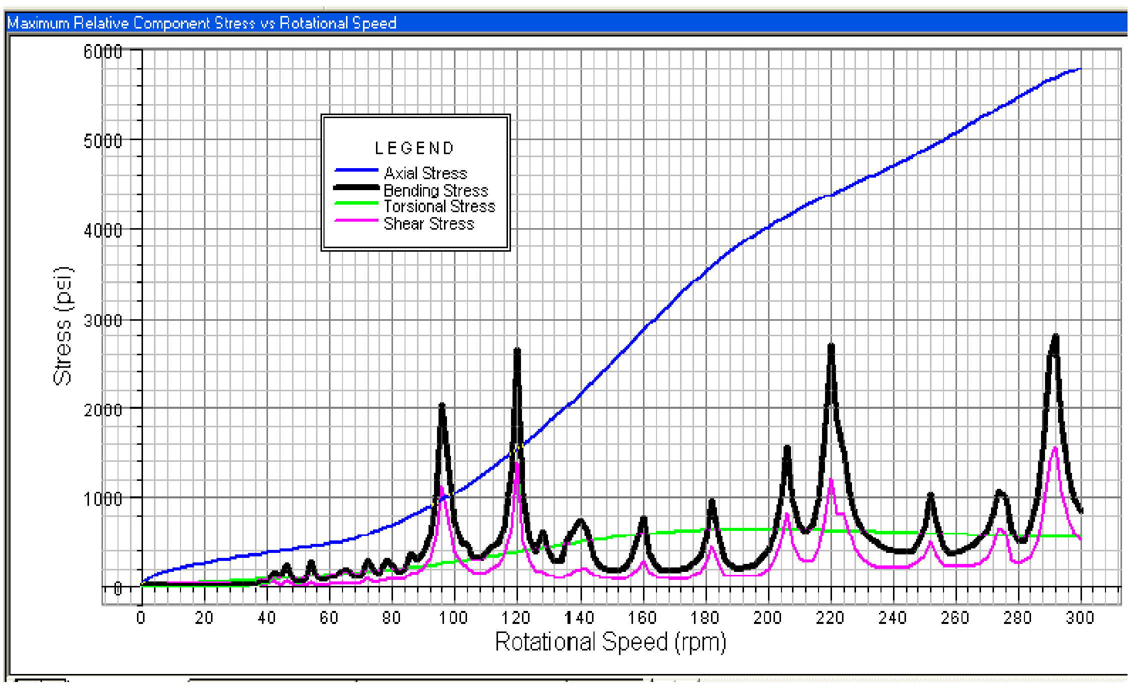
Appendix D



BHA Schematic (12 1/2") section

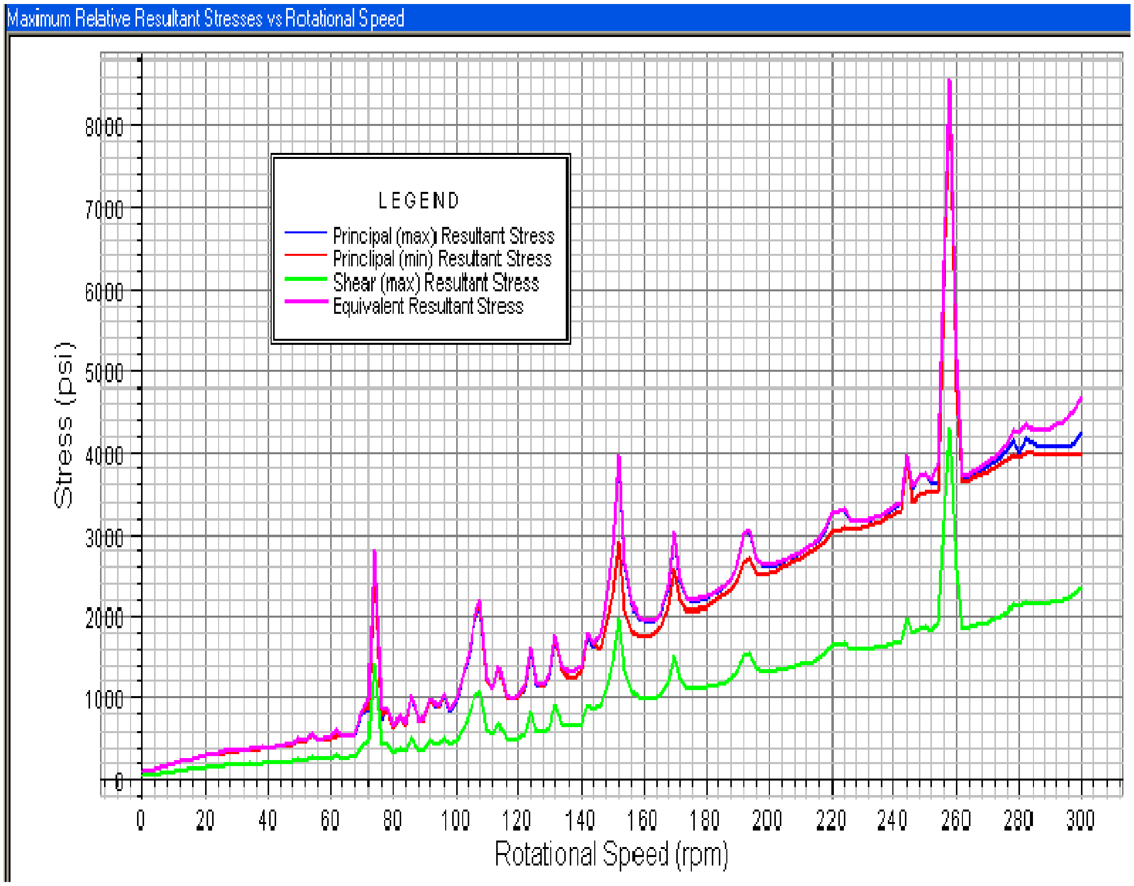
Appendix E



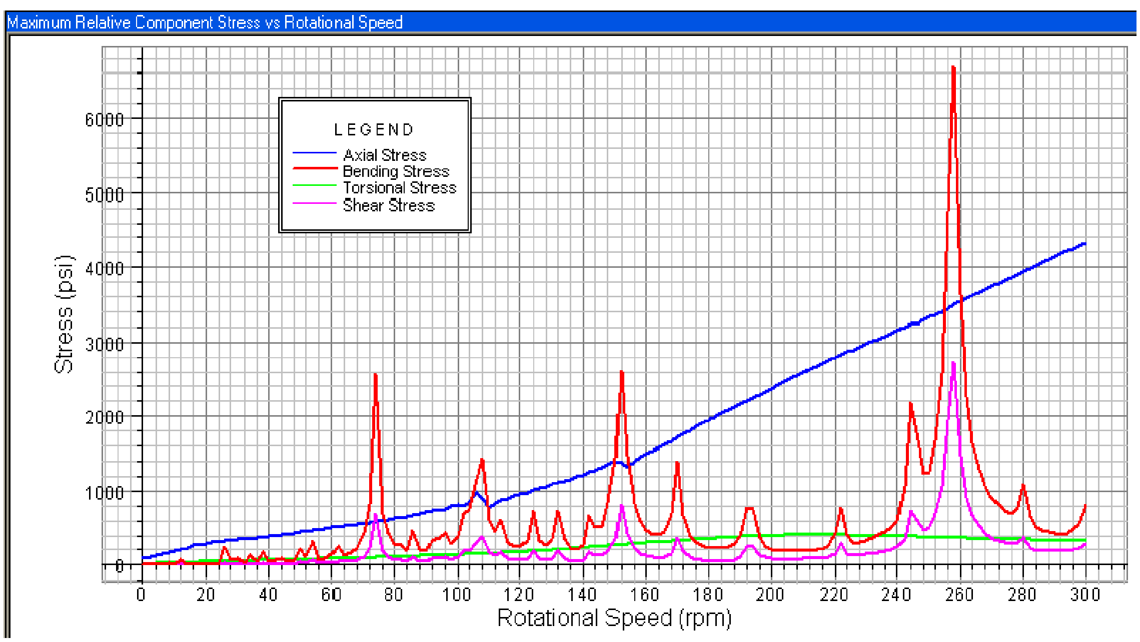


Max-relative resultant stress and max-relative stress components vs rotational speed (12 1/2")

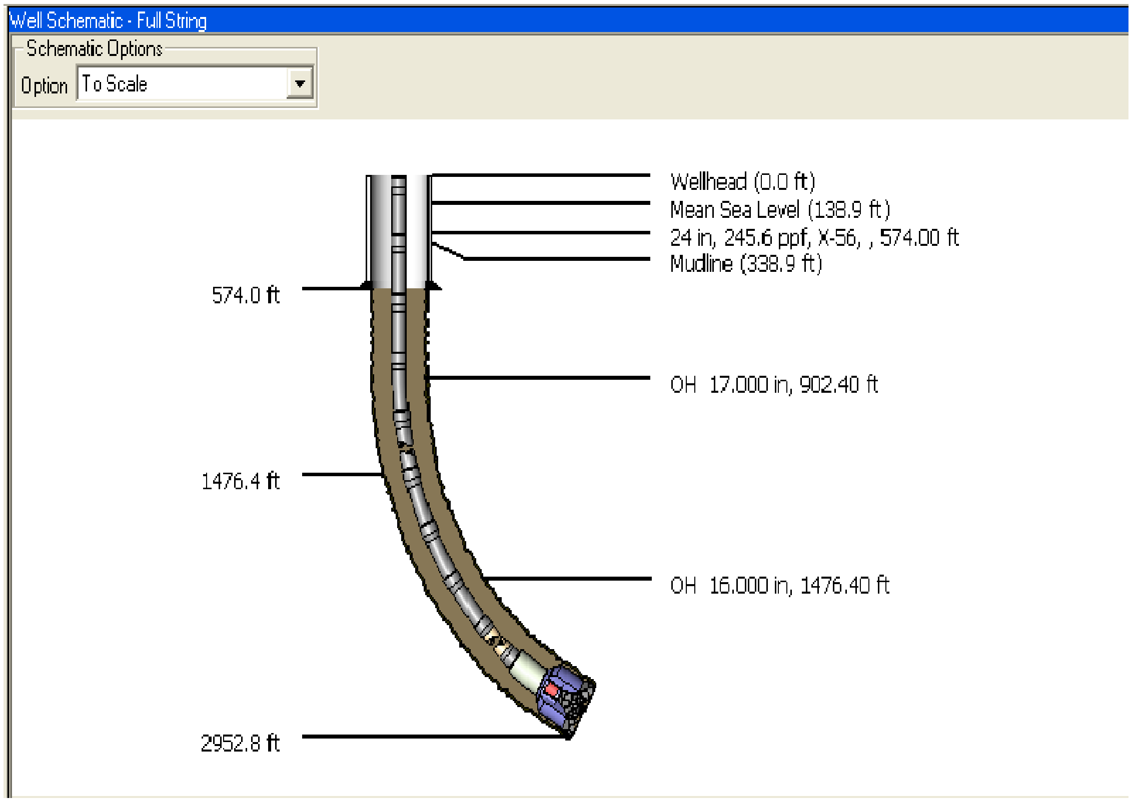
Appendix F



Max-relative resultant stress & max-relative stress components vs rotational speed (16") section



Appendix G



Well – Full String Schematic (16") RSS section