FATIGUE FAILURE PROGNOSIS OF AN OIL WELL DRILL STRING USING A LUMPED SEGMENT BOND GRAPH MODEL AND FINITE ELEMENT METHOD

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ABSTRACT

A novel methodology for fatigue failure prognosis of oil well drill strings is introduced which uses less computation power. A multibody dynamic Bond Graph (BG) model of a drill string and a Finite Element (FE) model are employed to estimate the remaining cumulative fatigue life of the drill string. The drill string with 2D lateral vibration and axial vibration is modelled in the 20 sim™ bond graph simulation environment with a body-fixed coordinate system. Drill string collision with the wellbore caused by a rotating imbalance is included in the BG model. Concurrently, a Computer-Aided Design model of the drill string is developed using Ansys® Structural, and it is then used in FE Analysis to determine the bending, axial, and shear compliances of each BG segment. The refined BG provides the bending moment history of the drill string back to the FE model to evaluate the remaining fatigue life.

Keywords: Bond Graph, cumulative fatigue, oil well drill strings, Finite Element Method

1. INTRODUCTION

1.1 The need for a fatigue failure prognosis technique

The urgent need for a fatigue failure prognosis technique has been present in the oil and gas drilling industry for several decades. As mentioned in (HIli *et al.*, 1992), 76 drill-string failures from 1987 to 1990 on three continents have been investigated. As illustrated in Figure 1, fatigue was estimated as the primary cause of 65% of these failures and had a significant impact on 12% of them. The other factors, such as excessive tension and torque, and low toughness of the material, were secondary causes of failures in comparison with fatigue. Supporting the above statistics, (Macdonald *et al.*, 2007) has mentioned that more than 50% of the drill string failures have occurred due to fatigue failure of the drill pipes. According to (Joosten *et al.*, 1985), during the same period, drill-string failures have occurred in 14% of all drill-rig systems and cost approximately US$ 100k each time the system experienced a failure.

Although the mechanisms of failures are well known and can be explained, the failure of drill strings still occurs. The prediction of drill pipe failure has become difficult because of the complex loading, severe vibrations, and the erosive and corrosive behaviour of the drilling mud (Zamani *et al.*, 2016). Therefore, the risk associated with drill string failure remains high in terms of probability of occurrence and the cost involved. This has motivated fatigue failure prognosis techniques of drill-strings.

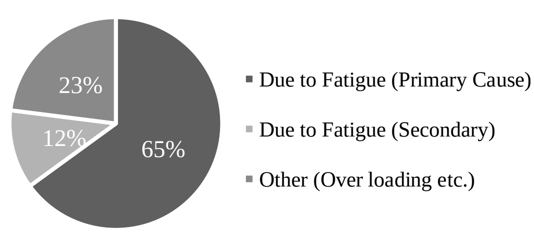


Figure 1: Drill string failures reported from 1987 to 1990 (HIli et al., 1992)

1.2 The reasons for fatigue failure of drill strings

Drill-strings used in oil drilling are subjected to complicated stresses due to excess vibration caused by bit bounce, stick-slip, and lateral forward or backward whirl with wellbore contact (Rideout *et al.*, 2015). These complex stresses make the drill -string vulnerable to failure due to cumulative fatigue. As described by (Zamani *et al.*, 2016), there are seven identified reasons for the initiation and propagation of fatigue cracks: surface irregularities; removal or flaking of drill pipe internal coating; drill string vibrations; frictional heating; stress corrosion cracking; sulfide stress cracking; and material defects during machining and heat treatment. Threaded connections in drill pipes are highly prone to stress concentration, which leads to fatigue crack initiation. This fact is highlighted in several studies including (Chen, 1990), (Grondin *et al.*, 1994), and (Knight *et al.*, 1999). Therefore, it is a must to consider the behaviour of threaded connections in fatigue failure prognosis.

1.3 The requirement of a hybrid model for fatigue prognosis

Fatigue failure prognosis can be performed following a numerical approach, such as FEA. Nevertheless, there can be constraints because of excessive simulation times (Rideout et al., 2015). On the other hand, a lower order Bond Graph (BG) model of a drill string may be able to predict the vibration behaviour of a drill string, but the localized stress and strain need to be calculated theoretically in post processing. The accurate theoretical calculation of those parameters becomes almost impossible when the geometries become complicated due to the presence of threaded connections and variable wall thicknesses. This can be handled using an FE model, by employing it in virtual experiments to determine the relevant material properties. Therefore, a combined approach of FE model and BG model is proposed to achieve this goal.

1.4 Fatigue estimation techniques

Fatigue life estimation of engineering components is an area with a number of open research topics. According to (Hancq & Browell, 2006), there are three main methods in fatigue analysis namely, strain-life, stress-life, and fracture mechanics.

Stress-life approach is an ideal for high cycle fatigue, which involves more than 10^5 cycles. This is performed based on empirical S-N curves and then modified by a variety of factors. Although the crack initiation and propagation are not separately identified, the method is suitable to determine the overall fatigue life of an engineering component.

The strain-life approach has several advantages over stress- life approach. The strain is directly measurable using strain gauges and has been identified as an excellent quantity for characterizing low cycle fatigue. This employs strain-life relation equations instead of S-N curves. Crack initiation and the critical plane of facture are important factors in this approach.

In the fracture mechanics approach, it is assumed that a flaw of a specific maximum size can be present anywhere in the component. It can be inside the material or on the surface. The maximum possible flaw size is decided by the precision of the non-destructive test (NDT) technique used. The propagation of the crack is determined based on the stress fluctuations acting on the body. The strength of this method is that the user can make decisions on the inspection intervals and scheduled maintenances.

According to the classification given in (Budynas & Nisbett, 2015) the three main categories of fatigue problems are: completely reversing simple loads; fluctuating simple loads; and combinations of loading modes. Completely reversed single stress situations can be handled with the S-N diagrams, relating the alternating stress to life. Only one type of loading is allowed here while the midrange stress must be zero. In the case of fluctuating simple loads, general fluctuating loads can be incorporated using a criterion to relate midrange (σ_m) and alternating stresses (σ_a). Criteria such as modified Goodman, Gerber, ASME-elliptic, or Soderberg can be employed while only one type of loading is allowed at a time. When there is a combination of loading modes such as combined bending, torsion, and axial it is required to determine the equivalent von Mises stresses for midrange stress (i.e. σ'_m) and alternating stress (i.e. σ'_a). Equations

(1) and (2) can be incorporated to determine these parameters and a suitable fatigue criterion can be employed to complete the fatigue analysis.

$$\sigma'_m = \left\{\left[K_{fB}\sigma_{mB} + K_{fA}\sigma_{mA}\right]^2 + 3\left[K_{fsT}\,\tau_{mT}\right]^2\right\}^{\frac{1}{2}} \quad (1)$$

$$\sigma'_a = \left\{\left[K_{fB}\sigma_{aB} + \frac{K_{fA}\sigma_{aA}}{0.85}\right]^2 + 3\left[K_{fsT}\,\tau_{aT}\right]^2\right\}^{\frac{1}{2}} \quad (2)$$

where subscript A, B, and C stand for axial, bending and torsion while K_f and K_{fs} stand for normal and shear modification factors respectively.

2. METHODOLOGY

The overview of the entire study is illustrated in Figure 2. Initially, two simulation models namely Bond Graph (BG) model and Finite Element (FE) model are employed. A detailed explanation on the two models are presented in 2.1 and 2.2. The FE model, which simulates a drill string repeating unit, is used to determine the axial, shear, and bending compliances. This was done by virtual experiments which were validated analytically. Those compliance values are then used to refine the BG as the first step.

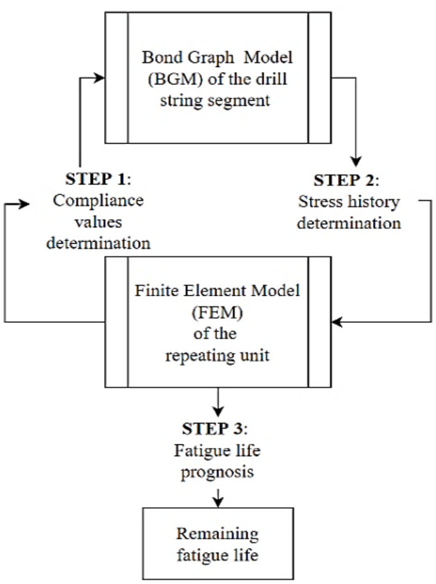


Figure 2: Overview of the approach

The BG model was verified using established theoretical calculations and using static deflection and dynamic response analysis. The BG model generates a bending moment history of the entire drill string of 100 m. This bending moment history is then fed back to the FE model as history data to be used in Fatigue Tool of Ansys® Structural for fatigue life prognosis. The estimated fatigue life through simulation was validated using standard stress-life analytical calculations.

2.1 The Finite Element Model

The FEA was done for the repeating unit of the drill string shown in Figure 3.a. The repeating unit is developed based on the schematic diagram of the drill string illustrated in Figure 4. It is an API 5D standard drill pipe with an outer diameter of 3.3 inches. The material is E75 Carbon Steel while the type of end finish is 'internal and external upset'. The middle part of the repeating unit consists of the threaded box and pin with two equal pipe segments connected to it. The element size was decided after conducting a grid dependency test and the minimum size of the element was determined as $5 \times 10^{-3}\ m$ considering the processing speed and convergence of the results.

The FEM model was used to fulfill two main requirements: firstly, to determine the compliance values and secondly to determine the remaining fatigue life based on the bending moment history as given by the BG model.

In determining the axial compliance, the element was cantilevered and subjected to a $1\ mm$ axial displacement (e_a). The reaction force (F_a) at the fixed end was measured using the probe tool. The stiffness (K_a) is the F_a per unit e_a, and the axial compliance (C_a) is the reciprocal of K_a. Following a similar approach, the shear compliance (C_s) was determined for a pipe segment and the threaded section separately. Short segments were taken to avoid bending effects while applying the shear force. The overall shear compliance was determined considering that the assembly is equivalent to springs in series.

Determination of the bending compliance (C_b) is not straightforward in comparison with the previous two. The cantilevered repeating unit was given a known bending moment, and the rotation of the cross-sections close to the free end was considered as illustrated in Figure 5. The

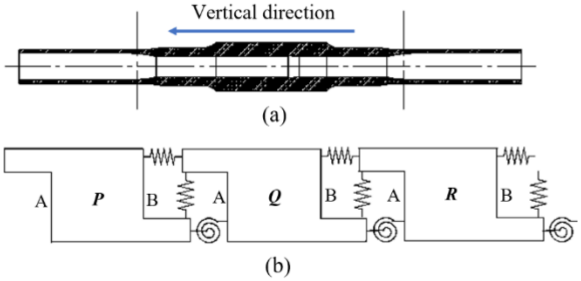


Figure 3: Discretization of the repeating unit (Not to Scale)

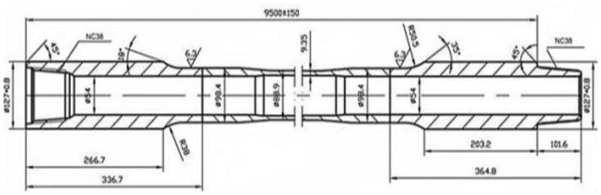


Figure 4: Schematic diagram of the drill (HongxinCreaton, 2019)

displacements of the points were drawn with high precision using AutoCAD® software and the angles of plane rotations were measured.

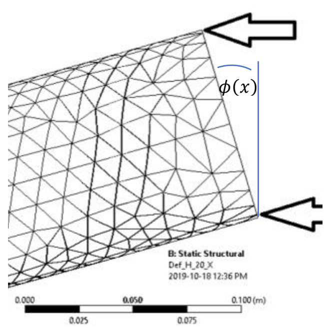
If the rotation of two cross-sections are $\phi(x)$ and $\phi\ (x + \Delta x)$, according to (Karnopp et al, 2012), the relationship between the applied bending moment (M) and the difference of the two rotations of the planes can be presented by equation (3). This is illustrated in Figure 6. Therefore, the bending compliance $\left(\frac{\Delta x}{EI}\right)$ is the required M for a unit change in $\phi(x + \Delta x) - \phi\ (x)$. The rotations of the cross sections were determined by measuring the displacements of specific nodes, and the bending moment was probed at the fixed end. The results of each compliance are presented in Table *1*.

$$M = \frac{EI}{\Delta x}\ [\phi(x + \Delta x) - \phi\ (x)] \tag{3}$$

The compliance values and the remaining fatigue life determined through the FE model were compared with the theoretical calculations.

2.2 The Bond Graph Model

The bond graph model is provided with pinned-pinned boundary condition by providing stiff springs $(e.g. 10^8 N\ m^{-1})$ at both the ends along with high damping coefficients $(e.g. 10^4\ Ns\ m^{-1})$. A zero-flow source is provided to keep the velocity at both ends zero. This is illustrated in Figure 7. Only the y velocity component is shown for clarity.



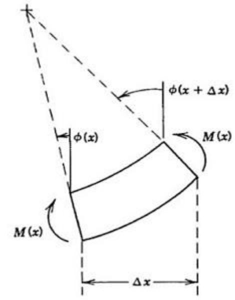


Figure 5: Bending stiffness determination experiment

Figure 6: Plane rotation (Karnopp *et al*, 2012)

As shown in Figure 3.b, the repeating unit of the drill string is discretized into three elements to be used in the BG. The element at the middle (***Q***) represents the threaded connection region with the varying wall thickness while the rest of the two (***P*** and ***C***) represent two similar pipe segments welded to the threaded connection. Other parameters used to implement the BG are tabulated in Table *1*.

Figure 8 illustrates the repeating unit of the 'Drill Pipe' indicated in Figure 7. There are thirty similar units inside the submodel 'Drill Pipe'. Nevertheless, the compliance values are not equal in all the elements as some represent the threaded connection while the others represent the pipe segments.

As shown in Figure 8, the repeating unit consists of the interface submodel and 2D element submodel. The function of the interface block is matching the lower endpoint (B) velocity values of n^{th}element to the top end (A) velocity values of the $(n + 1)^{th}$ element. In other words, the body-fixed velocity of the n^{th} element is converted to the velocity in the body-fixed coordinate system of the $(n + 1)^{th}$ element. The BG model of the *Interface (n)* block in Figure 8 is presented in Figure 9. A detailed illustration of the '*Element (n)*' submodel is given in **Error! Reference source not found.**. As shown, there are five terminals to that 2D model where two of them are for the top end translational velocities, another two for the bottom end translational velocities, and finally one for angular velocity about the z body fixed

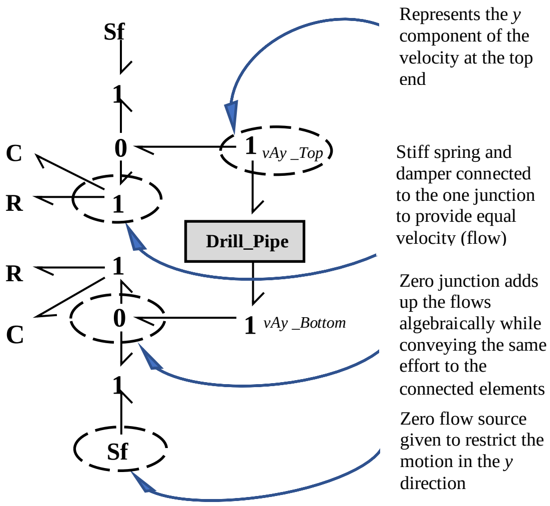


Figure 7: Boundary conditions of the BG model

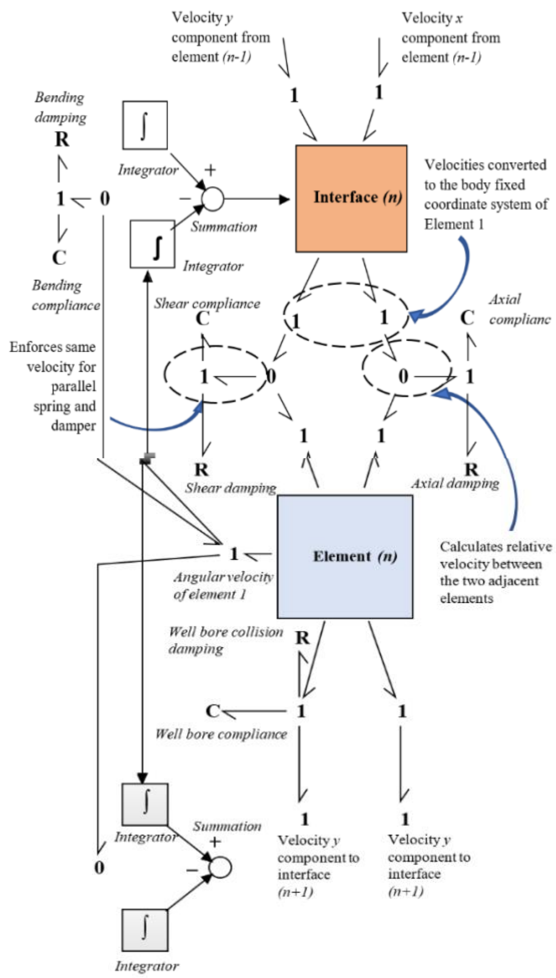


Figure 8: Repeating unit of the BG model

axis. A detailed explanation of this 2D element model can be found in (Jalali & Rideout, 2018). As shown in Figure 8, the angular velocities of each element are integrated and the difference of two integrals is taken at the summing junction. This provides the required input to the interface model. Further, in Figure 8, there are shear and axial compliances introduced at all the one junctions connected to the elements. Those two types are connected to the one junctions which represent x and y component of velocities respectively. Because, x is the axial direction of the element while y is the one perpendicular to that. The model does not include frictional effects generated from the wellbore drill string interaction. Nevertheless, the impact with the wellbore is simulated with the use of nonlinear contact springs on each lumped segment.

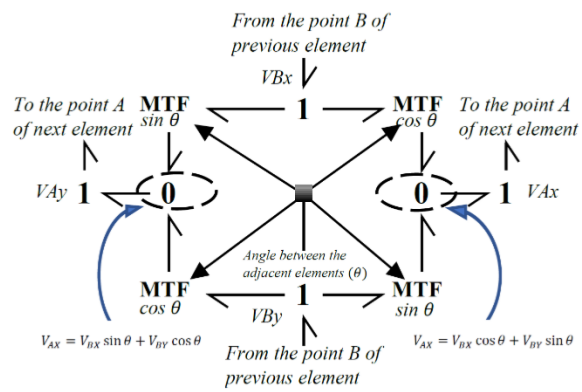


Figure 9: BG model of the Interface

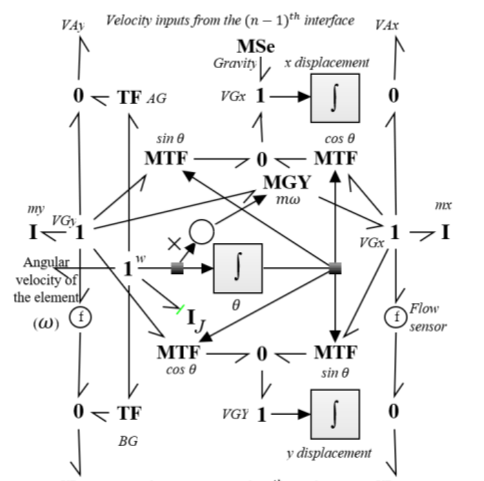


Figure 10: BG model of the 2D element

In, Figure 8, the 'well bore compliance' is employed for this purpose. It is coded such that the drill string experiences a force of, $k_{contact} \times \delta$, transverse to the drill string, when the displacement in the y direction is greater than or equal to the radius of the well bore. This condition creates a positive interference δ. The force is set to be zero in other instances.

2.3 Fatigue life estimation

Initially, fatigue life prognosis was performed using Ansys® Fatigue Tool, after simplifying the problem into a 'variable amplitude proportional loading' case. The simplification was possible as the point of interest in the drill string was close to the midpoint. This is because the force imbalance was located at the center of the drill string. This region of the drill string has near zero tensile stress as no external axial thrust was included in the simulation.

In the Ansys® fatigue simulation, the scale factor was set to 1 as the FE model was simulated for unit bending moment so the historical data need not be normalized. The BG was simulated for a known time period (10 sec) and the bending moment fluctuation was saved in a '*.dat'* file. Then the FE model was simulated with a unit bending moment (i.e. 1 N m) using Ansys® Static Structural. The simulated bending moment fluctuation from BG model shown in Figure 13 was then imported into the Ansys® Fatigue Tool to estimate the fatigue life. Figure 11 shows the sample bending moment fluctuation history exported from the BG model.

The fatigue life was also estimated using the stress-life approach presented in (Budynas & Nisbett, 2015) for a pure bending moment situation for verification. This was coded using Matlab® and can be expanded to analyzing a case where torsional and axial loadings are also considerable. The code takes the bending moment variation history from the BG model and performs rain flow counting to determine the mean and the range of the stress fluctuation as shown in Figure 12. Then it follows the standard calculation while considering the endurance limit modifying factors such as surface condition, size, load, and temperature. The same set of parameters and material data used in Ansys® Fatigue Tool were used.

Table 1: Specifications of the drill string segment used for simulation

Drill string parameters	**Value**	**Unit**
Pipe outer radius (r_p)	4.4×10^{-02}	m
Pipe segment length (L)	4.3×10^{-00}	m
Threaded segment length (L_t)	7.6×10^{-01}	m
Pipe axial compliance (C_A)	9.2×10^{-09}	$m\,N^{-1}$
Threaded segment axial compliance (C_{At})	6.8×10^{-10}	$m\,N^{-1}$
Pipe element bending comp (C_B)	3.8×10^{-08}	$\frac{rad}{N\,m}$
Threaded segment bending compliance (C_{Bt})	8.3×10^{-09}	$\frac{rad}{N\,m}$
Pipe shear compliance (C_S)	5.1×10^{-08}	$m\,N^{-1}$
Threaded segment shear compliance (C_{St})	6.7×10^{-09}	$m\,N^{-1}$
Well-bore contact stiffness ($k_{contact}$)	1.0×10^{-06}	$N\,m^{-1}$

The Matlab® code, BG, and FEM models are available in the author's online repository which can be accessed through

the link: (https://github.com/mihiranpathmika).

The fatigue strength factor (K_F) was taken as 0.9 and stress-life approach was employed with Gerber mean stress theory in both approaches. The analytical and Ansys® simulation results were closely in agreement and presented under results and discussion.

3. RESULTS AND DISCUSSION

A drill string fatigue failure prognosis technique makes an important contribution in risk reduction in oil drilling because there is a considerable probability of fatigue failure and high scale consequences are involved. Although there are numerical approaches such as FEM which can be implemented to perform this task, it requires a high computational power which makes the process slower. The proposed hybrid technique provides a solution for this issue by sharing the tasks among the two techniques, namely BG and FE models. The task sharing was done based on their respective strengths hence the overall process becomes efficient.

The remaining fatigue life of the critical point (maximum stress concentrated point) shown in Figure 13 was evaluated using both FEM model and theoretical calculations. The FEM model result was 26.3 hours while the theoretical result was 21.6 hours. Here, Figure 13. a illustrates the stress distribution in the threaded connection when the repeating unit FE model is cantilevered and loaded with a 1 N force at the free end. Figure 13. b represents the remaining fatigue life distribution over the threaded connection. The highest stress concentrated area has the lowest remaining fatigue life as expected.

3.1 Main challenges

One of the main challenges in developing the bond graph was the unavailability of published data and the experimental setups to validate the BG model. As mentioned under methodology, as a way around, the model was subjected to two virtual tests to improve confidence. Firstly, the natural frequency was determined through the frequency domain toolbox in 20 sim™. There, under model linearization, the effort on one axial compliance element was set as the input and the state of another element close to the midpoint of the beam was tested. The first, second, and third natural frequencies were compared with the theoretical values using Equation (4) (Rao, 2004). As shown in

Table 2, theoretical and simulation results were in good agreement for the first natural frequency. This improves the confidence in the dynamic behaviour of the drill string model to some extent.

$$\omega_n = \frac{n\pi c}{l}; \qquad n = 1, 2, 3 \ldots \tag{4}$$

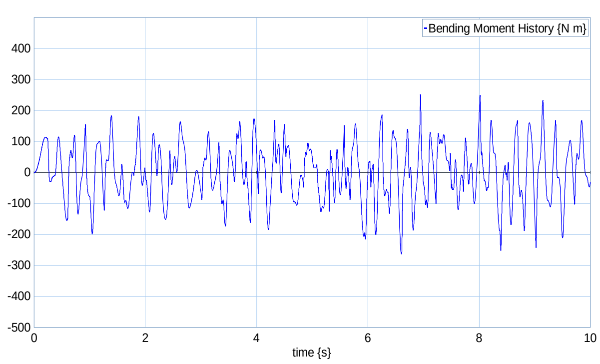


Figure 11: Bending moment fluctuation history determined through BG model

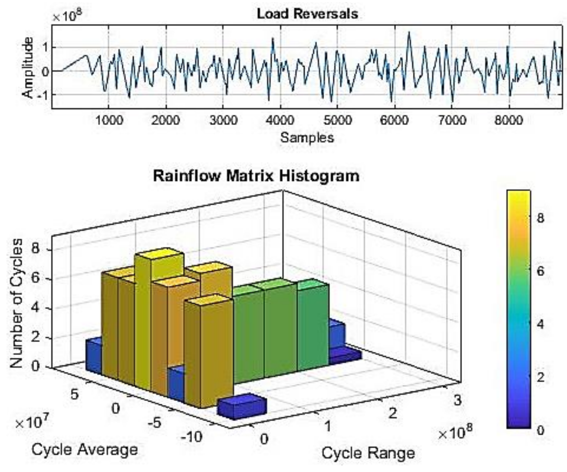


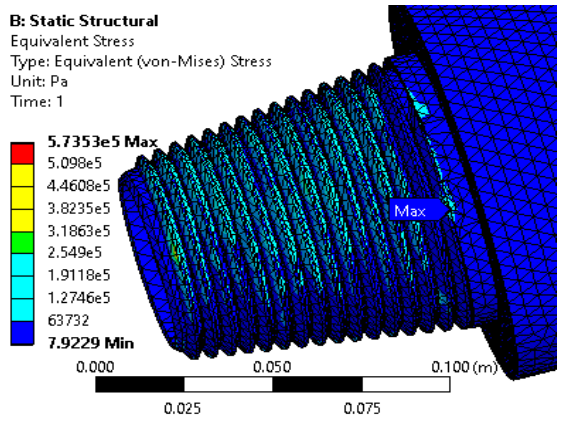
Figure 12: Rain flow counting result for a sample time of 10 s

Table 2: First three natural frequencies of the drill string

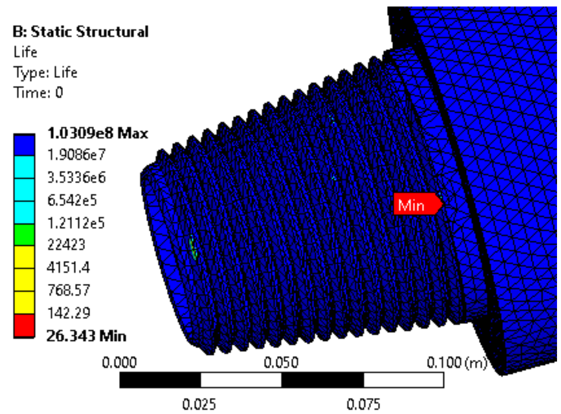
n	ω_n Theoretical (Hz)	ω_n Simulation (Hz)	Percentage deviation
1	170	169	0.6 %
2	340	289	15.0 %
3	510	404	20.8 %

Secondly, the beam was subjected to a three-point bending test and the lateral deflection at the mid-span was compared with the theoretical value. Equation (5) was used for the analytical calculations. In Equation (5), P is the applied load at the midspan; L is the length of the beam; E is the elastic modulus of the material; and I is the second moment of area of the cross section. The simulation results showed less than 1% deviation from the theoretical value helping to improve the confidence on the static behaviour of the BG model.

$$\delta_{max} = \frac{PL^3}{48EI} \tag{5}$$



(a)



(b)

Figure 13: Critical point of the threaded connection

The experimental validation of the FE model is quite challenging as the area of interest is the threaded connection. Therefore, the use of strain gauges is not practical. As mentioned in (Budynas & Nisbett, 2015), in a threaded connection, the first three threads take 75% of the total axial load. This was clearly evident by observing the fatigue damage in the first three threads in a separate FE model which is axially loaded. This is a good indication of the accuracy of the model. Further, the mesh was refined such that it gives a steady set of solutions which improves the confidence in the accuracy.

3.2 Limitations and potential applications of the BG model

The bond graph model is designed to capture the bending, axial and shear deformations only. It needs to be further developed to simulate the torsional deformations of the drill string. According to (Rideout *et al.*, 2015), this is an essential feature for a drill string simulation and will be addressed in future studies. Further, the frictional effects should be incorporated to get a deep insight of the behaviour of the drill string while in operation. A proper friction model can be incorporated to achieve this. In addition to that, a suitable bit-rock interaction model is to be introduced to simulate the interaction between drill bit with the rock being drilled.

This BG model can be adopted to predict the dynamic behaviour due to lateral and axial vibrations. Nevertheless, it is not recommended to use it when the torsional vibration induced vibrations, such as stick-slip, are dominant. Further, the BG model can be adopted in different applications which can be approximated to 2D plane deformation of beams such as leaf springs of vehicles.

3.3 Potential improvements in fatigue calculation technique

Fatigue calculation was initially done with Ansys® Fatigue Tool and then compared with the theoretical calculation for a simplified variable amplitude proportional loading case. There are a number of limitations involved with the methods used which can be further improved.

The drill string is subjected to a combination of bending, axial, and torsion stresses. As the BG used in the current study is two dimensional, the torsion is not considered because the main focus in this study is to develop the overall methodology. Here, the point of interest is a threaded connection closer to the center (i.e. the 15^{th} BG element) of the drill string. It can be seen in the BG that the drill string is in tension towards the top while the lower part is in compression as expected. The element 15 is in tension of 100 N, which creates normal stress of 22 Pa. Therefore, in comparison with the bending stress, this normal stress can be neglected. With this simplification, the problem can be approximated to a proportional, variable amplitude scenario, which can be handled with Ansys® Fatigue Tool. This allows comparing the two results from the theoretical calculation using Matlab® code and the Ansys® Fatigue Tool.

As a further development, the theoretical calculation can be generalized as follows to apply in combined loading applications. The bending moment, axial force and torsional fluctuation matrices of a given element can be extracted from the 20 sim™ simulation. Then it can be normalized and multiplied by the maximum direct and shear stresses determined by the FE model static analysis. Here it is assumed that the stress fluctuation is linearly related to the fluctuation of each load when their individual effect is considered. Knowing the direct and shear stresses in each direction, the bending induced 'signed von Mises stress' fluctuation matrix can be calculated. Then the 'rainflow' function in Matlab® signal processing toolbox can be used to perform the rain flow counting to determine the equivalent range (σ_a') and equivalent mean (σ_m'). Finally, the Palgram-Miner rule can be implemented to determine the damage percentage and the remaining lifetime (prognosis) of the drill string.

4. CONCLUSION

A multibody dynamic Bond Graph (BG) model of a drill string and a Finite Element (FE) model were employed to estimate the remaining cumulative fatigue life of a drill string. FE model was incorporated to refine the BG model compliance values in order to increase the accuracy of the BG model. The updated BG model was used to extract the dynamics of the drill string. The dynamic response of the drill string was then converted to stress fluctuations and used in fatigue analysis using both analytical and FE model. The remaining useful life was prognosed as 26.3 hours by the FEM fatigue tool and was verified analytically.

In general, the proposed BG–FE model hybrid approach can be effectively used in fatigue failure prognosis of drill strings while FEA can be effectively used to parameterize the BG simulations to increase precision.

5. FURTHER WORK

The BG model developed in this study is a 2D model hence only two of the six main borehole assembly (BHA) dynamic motions can be simulated. Simulation of rest of the types of motions including forward and backward whirl, and torsion can be achieved by developing a 3D BG model. The procedure followed and proposed for combined loading in the current study can be used in determining the remaining fatigue life. Further to that, the model is to be experimentally validated. As an alternative, an FE transient model of a complete drill string can be developed and compared with the performance of the hybrid model proposed in the current study. On the other hand, the fatigue analysis can be broadened to a multiaxial critical plane approach to make it more accurate in fatigue failure prognosis.

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