Real-Time Fatigue Risk Assessment of BHA Connectors Using Combined Physics and Data-Driven Approach

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ABSTRACT

Drilling operations depend not only on controlling surface parameters but also on keeping bottom-hole assembly (BHA) components structurally sound. The BHA is the lower portion of the drill string in a drilling operation – the part that actually contacts the wellbore and guides the drilling process. Failures, especially at the connection between the flow diverter and the drive shaft behind the mud-motor power section, can cause major non-productive time (NPT), high costs, and poor performance. These failures are often linked to combined surface and downhole rotational speeds and high bending moments, which are common during directional drilling. To reduce this risk, we present a new method for real-time health monitoring and remaining useful life (RUL) estimation of these connections. The method combines physics-based fatigue modeling with machine-learning estimators, making it possible to track connector use across time and jobs using serialized component data. The system processes real-time drilling parameters to estimate downhole rotational speed (RPM) and bending moment. When measurement-while-drilling (MWD) data are available, direct RPM values are used; otherwise, a predictive model based on temperature, flow rate, and differential pressure is applied. Bending moment is inferred from drilling parameters and BHA design. The framework then calculates fatigue damage with connector-specific S–N (stress–number of cycles) curves and updates both current and cumulative RUL values. This helps operators make proactive decisions and lowers the risk of expensive failures. Tests with historical drilling data show strong agreement between predicted damage and observed connector failures, proving that the approach works in the field. The solution is already integrated into a commercial platform and used by field teams. Case studies show it reduces unexpected failures, cuts non-productive time, and improves the efficiency of directional drilling.

1. INTRODUCTION

Drilling operations are a fundamental aspect of the oil and gas industry, used to extract hydrocarbons from the subsurface. The process involves creating a wellbore using a rotating drill string. This drill string consists of a Bottom Hole Assembly (BHA) and drill pipe, which connects to the rig's surface equipment. The BHA includes components such as the drill bit, downhole mud motors and/or other steerable tools, various measurement and logging tools, stabilizers, and drill collars. Each component, from the drill bit to the surface equipment, is connected via threaded connections.

If any connection within the drill string fails and causes the string to come apart, a Lost in Hole (LIH) event occurs, where part or all the BHA is left downhole. LIH events are extremely costly for oil and gas operators because they lead to significant non-productive time (NPT) to retrieve the lost components (known as "the fish") and can even result in the loss of the financial asset (the wellbore) if recovery is unsuccessful. In such cases, the operator not only loses the cost of drilling the well but also forfeits potential future production revenue. For these reasons, preventing LIH events is a high priority.

The most common cause of connection failure is fatigue. As the BHA rotates and torque is applied to the drill bit, torsional fatigue becomes the dominant failure mode. Analysis of such failures indicates that these connections are often subjected to the greatest bending loads. Small-scale damage and crack formation commonly develop on the affected connectors due to the repeated tension and compression cycles induced by the rotating, curved structure of the BHA (see Figure 1). The intensity of strain and stress is strongly influenced by the shape of the well path, with elevated fatigue damage frequently observed in curved intervals, particularly in zones with high Dog-Leg Severity (DLS). DLS in drilling is a measure of how sharply the wellbore changes direction over a given length. The related specific type of LIH event is referred to as a twist-off. A twist-off can occur at any single connection or at multiple connections within the drill string. One particularly vulnerable BHA component is the downhole mud motor.

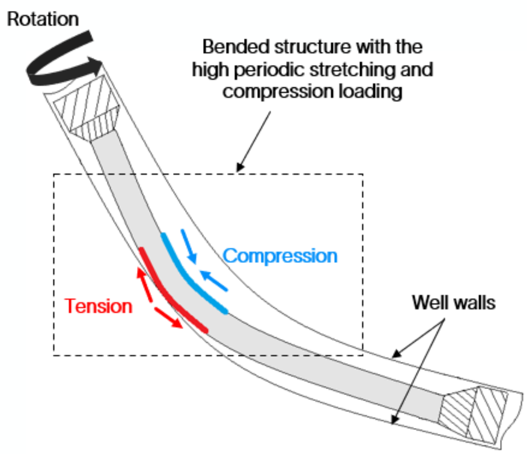

Figure 1. Schematic illustration of drill string loading while drilling a well section with high dogleg severity.

Mud motors are hydraulically powered volumetric motors that rotate the drill bit independently of the drill string above. These motors are steerable tools designed to guide the wellbore along a planned trajectory, typically at non-vertical angles. This technique – directional drilling – enables more effective access to complex reservoirs and improves hydrocarbon recovery.

To enable this independent rotation, mud motors contain internal mechanical components. To accommodate these, the motor housing often has thinner walls, and the internal parts are generally smaller than those found in other BHA components. These two factors – the reduced wall thickness of the housing and the smaller internal component dimensions – make mud motors more susceptible to twist-off failures compared to other parts of the BHA.

One internal connection particularly prone to failure is the driveshaft–flow diverter interface. Both the driveshaft and the flow diverter are components of the drivetrain responsible for rotating the drill bit independently of the drill string (Figure 2). The driveshaft, powered by the motor's transmission, transfers rotational force to the bit. It is engineered to withstand significant axial and radial loads with the support of upper and lower radial bearings and the bearing pack. The driveshaft is connected to the transmission section via the flow diverter.

The flow diverter, also referred to as a coupling, serves as the critical link between the driveshaft and the transmission. It is torqued to the upper driveshaft threads on one end and to the transmission shaft on the other. The flow diverter also contains a bypass port, allowing most of the drilling fluid to pass through the motor's internal diameter, while a smaller portion is diverted to the lower end internals, including the bearing pack.

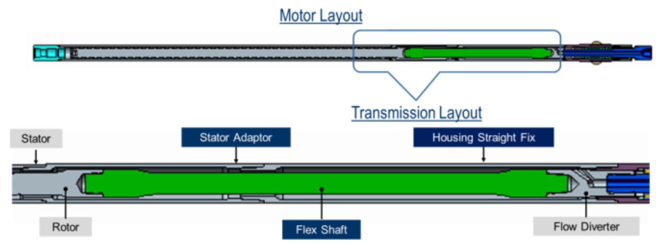

Figure 2. Illustration of mud motor and transmission layout in the BHA.

2. BACKGROUND AND LITERATURE REVIEW

The structural integrity of BHA components is pivotal to safe and efficient drilling operations. Yet in practice, most health monitoring of critical BHA connectors still relies heavily on visual inspections. Naked-eye examinations can reveal obvious fatigue cracks or thread damage, but they often miss early discontinuities and subtle crack initiation sites (Vaisberg, Vincké, Perrin, Sarda, and Faÿ, 2002). This limitation means that impending failures can go undetected until they become severe. Recent twist-off failures at internal mud-motor connections (e.g. the flow diverter to driveshaft coupling) have underscored the shortcomings of traditional maintenance strategies. Such incidents highlight broader weaknesses in the health-monitoring ecosystem for BHA connectors, where purely visual or periodic checks are not enough to prevent catastrophic breakages.

Conventional BHA surveillance techniques provide only coarse indicators of equipment's health. Drillers typically monitor surface torque and drag trends and downhole vibration logs, supplemented by periodic nondestructive inspections (such as magnetic-particle testing of threads). While these methods can detect gross anomalies or damage that has already occurred, they do not quantify cumulative fatigue damage as it accumulates in real time. In most cases, fatigue life is estimated offline, after the fact. Engineers estimate how close a tool is to failure by using S–N (stress–number of cycles) curves and Miner's damage rule. They may also run finite element stress analysis based on the measured Dog-Leg Severity. These analyses are informative but not performed continuously during drilling. In fact, commonly used fatigue tracking methods often reduce complex loading history to simple metrics like rotating hours, without accounting for actual bending stress or load cycles encountered downhole (Mills, Menand, and Dao, 2018). This gap leaves drillers effectively blind to how quickly damage is accruing during operations.

Data-driven prognostics are beginning to augment these traditional models. Recent studies have combined physics-based fatigue models with machine learning (ML) techniques – including recurrent neural networks (RNNs), gradient-boosted tree ensembles, and even Digital Twin models – to predict the RUL of high-stress drillstring components (Belov &Chen, 2023). For example, hybrid approaches have been used to successfully estimate RUL for outer mud-motor housings and drill-pipe tool joints by integrating real drilling data with model predictions (Belov, Chen, Liland, and Malik, 2025). These efforts demonstrate the potential of predictive analytics in drilling: by learning from historical data and simulations, such systems can warn of an impending fatigue failure before it happens. However, to date these digital fleet-management programs have been applied mainly to external components like motor housing. They seldom extend to internal BHA couplings, which face different challenges.

Internal BHA connectors (such as drive shafts, couplings, and flow diverters) present a tougher monitoring challenge than outer housings. These internal connections typically have thinner wall profiles and more complex load paths, making them especially susceptible to high-cycle fatigue under torsional and bending loads. Ironically, these parts often operate at relatively low nominal stress, but their geometric stress concentrators and constant vibration can initiate microscopic cracks that grow over time. Post-mortem failure analyses routinely reveal classic fatigue patterns on these connector fracture surfaces – for instance, ratchet marks caused by multiple micro-cracks coalescing (Figure 3). Such features are telltale signs that the failure evolved from many stress cycles (high-cycle fatigue) even though the operating stresses were not extreme.

Field experience corroborates how quickly fatigue damage can accumulate in these vulnerable spots. In one internal documented case, a mud-motor connector in a well's section with an exceptionally sharp Dog-Leg Severity consumed nearly its entire fatigue life in a matter of hours. DLS locally exceeded 15 deg per 100 ft in that scenario, generating intense bending stresses; the consequence for fatigue life was dramatic, as even a single high-DLS interval significantly eroded the connector's usable life. This kind of incident starkly illustrates the need for continuous, real-time tracking of fatigue at the connector level. Traditional periodic checks or end-of-well analyses are simply too late – by the time a crack is visibly detected, or a life calculation is performed, the component may be on the verge of twisting off.

Considering these challenges, recent literature and field reports highlight several critical gaps in the status quo of BHA connector management. In particular, three deficiencies stand out:

1. No Real-Time Fatigue Metrics: There is a lack of real-time monitoring for fatigue damage accumulation at the connector level. Drilling crews currently have no direct sensor or indicator to track how much fatigue life has been expended during operations, hour by hour or minute by minute.
2. Poor Integration of Physics and Data: Existing workflows only loosely integrate physics-based damage models with streaming operational data. Stress and fatigue predictions are often made offline, without continuously ingesting measurements from the rig (such as weight-on-bit, RPM, or downhole accelerations) that could update damage estimates in real time.
3. Limited ML Models for Mud-Motor Loads: Current machine-learning frameworks are not tailored to the unique load spectra and failure modes of mud-motor drivetrains. Models trained on general drillstring data may not capture the combined torsional, bending, and pulsation loads that internal motor connectors experience. There is a need for prognostic models specifically tuned to predict fatigue in these complex conditions.

These gaps leave a dangerous blind spot in drilling operations. Without real-time fatigue tracking and a unified physics/ML approach, operators risk running connectors to the point of failure unknowingly. The consequence, a sudden twist-off, can lead to costly downtime, fishing operations, or even well-related control issues if the BHA is left in a vulnerable state.

Figure 3. Optical fractographic photos of the fracture surface of the failed driveshaft. Evident beach marks with the single origin at the root of the last engaged thread were revealed. The fracture surface was relatively flat with one ratchet mark present next to the fatigue origin.

3. METHODOLOGY OVERVIEW

To address the above deficiencies mentioned in the previous part of this paper, we propose a Prognostics and Health Management (PHM) methodology that fuses real-time data with advanced fatigue modeling. The core idea is to combine bending-stress proxies derived from both surface measurements (e.g. hook load, torque, and drilling parameters) and downhole sensor data (from measurement-while-drilling tools) into a unified damage-tracking model. These stress and load proxies serve as continuous inputs to a hybrid fatigue model that couples traditional physics-based rules with machine learning algorithms. For example, the model might use a finite-element derived stress influence factor for each connector, but continually update the fatigue damage using streaming data, adjusting the cumulative damage index on-the-fly as conditions change. By blending physics with data-driven insights, the PHM system can produce real-time estimates of each connector's remaining useful life. These RUL calculations are visualized for the drilling team in real time, providing an intuitive health gauge for the connector. In essence, the system functions similarly to a digital twin of the BHA connector – it continuously assimilates data and updates the predicted damage state with uncertainty bounds. Field trials of similar digital models have shown that tracking fatigue life during drilling is feasible and can reliably indicate when a component's RUL falls below a safe threshold. Armed with this information, drillers and engineers can make proactive decisions: for instance, adjusting drilling parameters, rotating off a high-stress trajectory, or pulling out of hole early to replace a connector before a twist-off occurs. This contrasts sharply with the reactive, after-the-fact approach of traditional maintenance. In summary, the proposed PHM approach directly targets the identified gaps by providing:

- Real-time fatigue accumulation metrics at the connector
- Tight integration of physics-based damage modeling with live operational data streams
- Machine learning models trained on mud-motor-specific load cases to address scenarios with limited downhole data.

By implementing such a system, the industry can significantly enhance the structural health monitoring of BHA connectors. The outcome will be fewer unexpected failures, improved safety, and more efficient drilling operations – a tangible step forward in both academic research and industry practice toward truly predictive maintenance in drilling.

3.1. System Architecture and Used Methods

An in-depth investigation into the failure modes of critical connectors within the BHA has established a clear correlation between applied bending moments and the connectors' projected fatigue lifespan. Consequently, a key objective of the relevant PHM workflow is to estimate the fatigue endurance of each specific connector type throughout the drilling operation, as a function of the corresponding bending moment encountered.

To enable this estimation, the model must continuously track three essential variables: the magnitude of the bending moment, the expected fatigue life of the connector under that load, and the rotational speed of the connector in revolutions per minute, which reflects the rotational behavior of the BHA at the surface and/or the output rotation of the mud motor power section (depending on the type of the considered BHA connector). This rotational speed is especially critical, as it enables the conversion of fatigue cycles into time-based estimates.

The algorithm operates by estimating the expected fatigue resource of a specific connector for each time interval, where each interval corresponds to the drilling of a small depth segment (…, i–1, i, i+1, …) along the well trajectory (see Figure 4). The length of a given drilling segment is influenced by the consistency of critical operational parameters and adjusts dynamically in response to their variability. Within each of these depth intervals, the expected fatigue life is calculated using the average drilling parameters. This allows the algorithm to determine the portion of the connector's fatigue resource consumed during that interval, based on its duration.

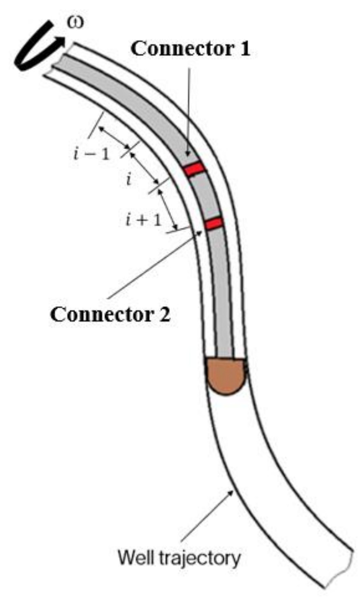

Figure 4. Interval-based fatigue resource estimation along the drilled well trajectory.

The relationship between operating conditions and the fatigue durability of connectors has been established through numerical modeling. Fatigue resistance is influenced by several factors, including connector geometry, material properties, and the prevailing drilling environment. To derive the required fatigue curves – depicting the relationship between bending moment and the number of cycles to failure – Finite Element Analysis (FEA) was employed in combination with a strain-based fatigue model. A more detailed description of the methodology used will be provided in the following section of this paper.

Accurate fatigue life estimation within the PHM framework for high-stress connectors requires knowledge of the bending moments acting on the BHA. These moments are strongly influenced by the configuration of the wellbore and the spatial location of the connectors. However, obtaining direct measurements of the bending moment is impractical due to the influence of multiple interdependent factors such as the stiffness of the BHA, borehole profile, and operational drilling parameters. To overcome this limitation, the algorithm incorporates a drilling dynamics simulation engine (Chen, Shen, and Yun, 2018), developed in-house at SLB. This simulator is a sophisticated modeling environment based on a three-dimensional nonlinear finite element framework, capable of representing the full drillstring while accounting for detailed BHA architecture, well trajectory, and real-time drilling inputs. It provides precise estimates of the bending loads experienced by each connector. More details about it will be provided later in this paper.

An overview of the PHM solution tailored for critical BHA connector evaluation is presented in Figure 5. The step involving the estimation of mud motor output rotational speed based on operational drilling parameters (such as flow rate, downhole temperature, and differential pressure) is optional within the workflow and is only applied when direct downhole measurements of rotational speed are not available in the dataset. More information about used machined learning model of the mud motor power section can be found in Belov, Rocchio, and Zhang (2023).

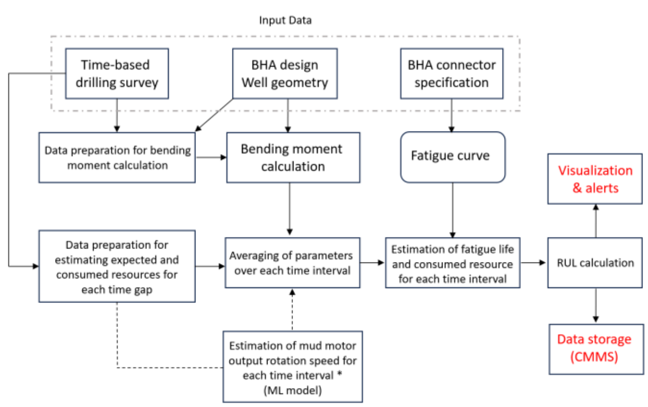

Figure 5. High-level architecture of the PHM solution for BHA connectors.

The system leverages inputs such as surface drilling measurements, BHA configuration data, directional survey records, connector specifications, and the axial distance between the connector and the bit. For each time-based step, the algorithm integrates the calculated bending moment, surface parameter values, and/or downhole data (such as mud motor rotational speed) to assess instantaneous fatigue damage. In cases where downhole measurements are unavailable, the mud motor rotation speed is estimated using surface data in combination with a machine learning model developed for the mud motor power section. This model predicts the expected output parameters of the motor. Cumulative fatigue consumption is then used to project the RUL of the connector, which supports operational decision-making and proactive condition-based planning.

The estimation of RUL (denoted as Ψ) within the PHM framework follows a clear and effective methodology, as outlined in Equation 1. The model references a connector-specific fatigue curve to determine the proportion of fatigue life expended during each time segment – typically lasting between 30 and 180 seconds, depending on the duration and dynamics of the drilling operation (considering the stability of average drilling parameters over the interval). These short intervals enable precise tracking of fatigue accumulation over time. The total fatigue consumed is calculated by summing the percentages from all intervals, and this value is subtracted from the connector's original fatigue capacity to estimate its RUL. This continuous evaluation strategy supports real-time health monitoring of BHA connectors, allowing for proactive maintenance actions that help reduce failure risks and improve overall drilling performance.

$$\Psi = 100\left(1 - \sum_{i=1}^{K} \frac{\Delta t_i \omega_i}{N_i}\right) \tag{1}$$

Equation (1) represents the computation of the accumulated RUL Ψ for BHA critical connector, where K – number of time gaps, i – considered time interval, Δt_i – duration of the considered time interval, ω_i - average rotation speed of the drill string for the considered time interval i, N_i – the number of fatigue cycles connectors can endure before failure under the existing average bending moment over the specified time interval i.

The PHM model developed for critical BHA connections provides RUL estimates tailored to each individual external or internal connector, enabling informed and timely decisions on component retirement to prevent expensive failures. This enhanced PHM approach represents a major advancement in predictive maintenance strategies for BHA connectors. By combining finite element–based fatigue evaluation with modern simulation tools, the model offers a highly accurate and adaptable framework capable of accommodating diverse drill string designs and a wide range of operational conditions.

3.2. Real-time Data Collection

A critical component of the real-time PHM solution discussed is the reliable collection and processing of real-time data. Two primary data types are utilized. The first type is surface data—information recorded by sensors located on the rig that reflect the system's response. Examples include flow rate, surface rotation speed of the drillstring (from the surface motor), hookload, and others. These surface measurements are typically available at high frequency (usually around 5 Hz) and are easily accessible to users, especially at the rig site.

The second type is downhole data, typically collected by MWD (Measurement While Drilling) or LWD (Logging While Drilling) tools. These measurements reflect local operating conditions and the health status of downhole components. Examples include downhole temperature, bit rotational speed, and tool vibrations. The data is typically stored in the tool's internal memory and becomes fully available in high resolution only after the BHA is retrieved from the well. While high-resolution data are collected, real-time transmission during drilling is limited by the capabilities of mud-pulse or electromagnetic telemetry systems. These limitations result in lower-frequency transmission (typically between 0.02 and 0.2 Hz), and only a subset of the recorded channels can be sent in real time due to bandwidth constraints. This necessitates data prioritization and introduces accuracy limitations that must be considered in the development of any PHM algorithm based on real-time data streams.

Another important consideration is that real-time monitoring of rig equipment, including the drillstring and BHA, is typically conducted remotely – often outside the drilling site. Figure 6 illustrates the high-level architecture of the real-time PHM workflow. In such cases, all essential surface and downhole data are transmitted via satellite, cellular, or other Internet connections to a remote performance or maintenance center. This setup requires data pre-processing at the rig, including synchronization of surface and downhole data, noise filtering, and resampling. As a result, the standard data sampling interval used for real-time monitoring typically ranges from 3 to 10 seconds.

Fortunately, practical experience has demonstrated that this level of data resolution is well aligned with the physical timescales of fatigue and degradation processes in BHA connectors. Therefore, the chosen sampling rate provides sufficient accuracy and reliability to support the objectives of the proposed PHM algorithm, ensuring meaningful and timely health assessments in the field.

The important component of the real-time solution is the cloud-based Computerized Maintenance Management System (CMMS), which contains all the necessary information about the current drilling job as well as the results of all previous equipment utilization, retrievable by serial numbers. It allows tracking each unique part from job to job and calculating the RUL by taking into account the resources consumed in previous runs.

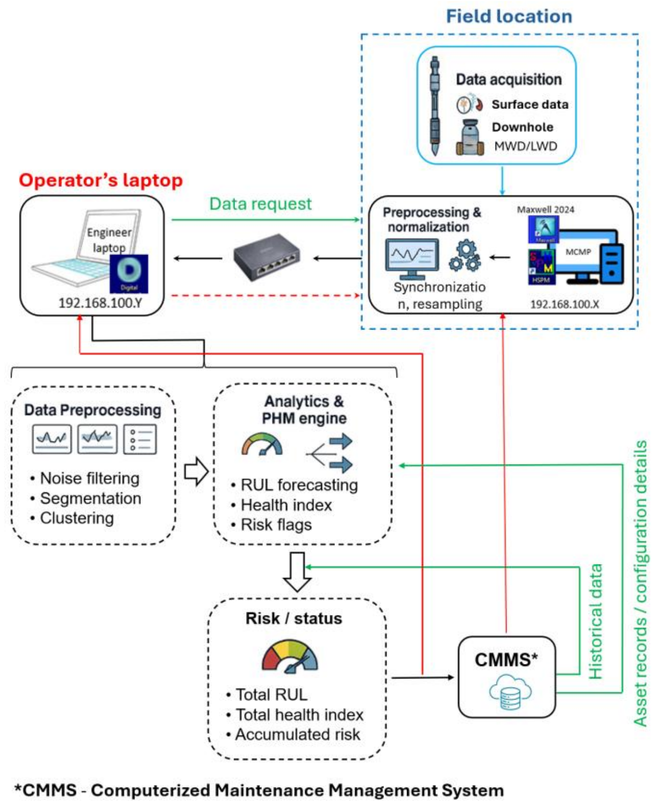

Figure 6. High-level architecture of the real-time PHM workflow.

4. FATIGUE CURVE ESTIMATION METHODOLOGY

The fatigue curve estimation methodology consists of two parts. First, finite element analysis (FEA) was applied to calculate stress and strain variations under cyclic bending load conditions. Second, the FEA results were post-processed to generate the fatigue curve.

4.1. Finite Element Analysis

Three-dimensional (3D) finite element analysis was conducted to evaluate the deformation of the threaded connection under cyclic loading. Due to the assembly's plane symmetry, a half-model was constructed to reduce computational costs for majority of the connectors. In this section, the simulation of the drive shaft/flow diverter connector is presented as an example.

Figure 7 presents the details of the 3D FEA model, which spans from the top of the flex shaft to the bottom of the drive shaft. The model includes the flex shaft, flow diverter, drive shaft, spacer, bearing components, and housing. The thread profile was explicitly modeled at the critical location—the threaded connection between the flow diverter and the drive shaft. To further optimize computation, other thread connections were simplified as bonded interfaces.

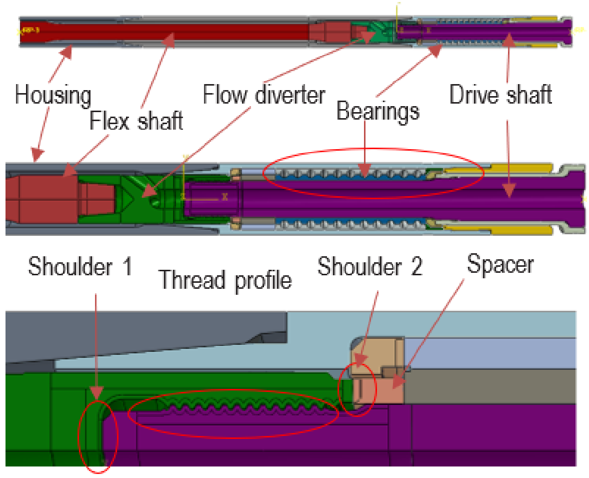

Figure 7. Finite element analysis model setup.

Material properties for each component were assigned based on elevated operational temperatures (350°F). An elastic-plastic analysis was performed using isotropic hardening material models.

Figure 8 displays the meshing scheme of the model. A combination of second-order hexahedral and tetrahedral elements was employed, with mesh refinement focused on critical regions—specifically, the thread roots at the flow diverter and drive shaft connection.

Frictional contact interactions were defined between components. A coefficient of friction (CoF) of 0.08 was applied at the threaded interfaces, while a CoF of 0.1 was used for other contacts, based on laboratory test data.

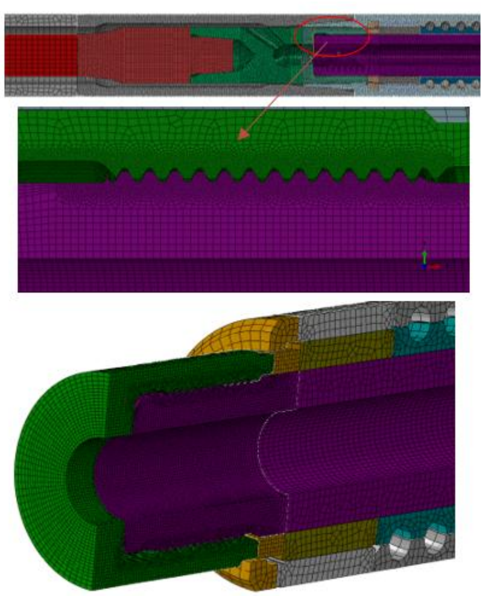

Figure 8. FEA mesh assignment.

FEA loading conditions are illustrated in Figures 9.

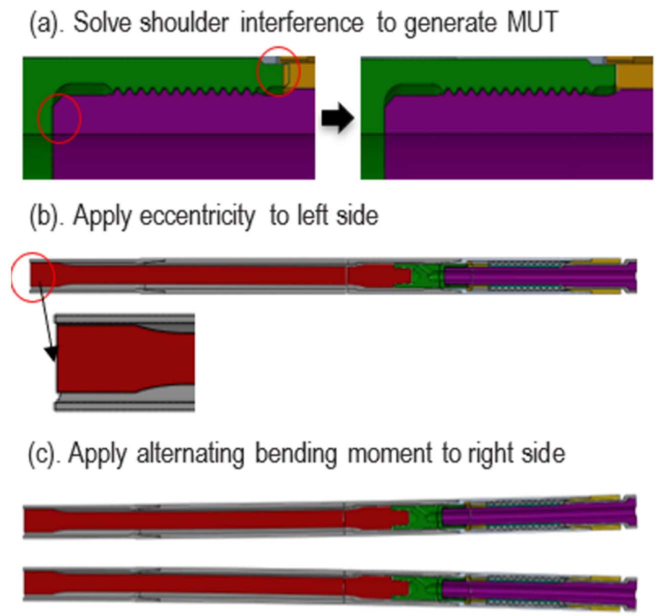

Figure 9. FEA loading conditions.

A plane symmetry constraint was imposed along the symmetric surface. The left end of the assembly (top of the flex shaft) was fixed. Loading was applied in the following sequence:

4. Make-up torque (MUT) was introduced by resolving the interference fit predefined at the thread shoulders.
5. The left side of the flex shaft was displaced vertically to simulate eccentricity induced by the rotor in the motor power section.
6. A single fatigue cycle of alternating bending moment was applied at the right end (bottom of the drive shaft), consisting of upward and downward bending.

The entire procedure was modeled as quasi-static and simulated using Abaqus Standard 2022 commercial software.

4.2. Fatigue Curve Postprocess

Post-processing was then applied to convert the FEA results into fatigue curve predictions. The stress and strain results at the flow diverter and drive shaft threaded connection were extracted from the FEA. Fatigue life was calculated through multiaxial fatigue analysis using the Brown-Miller algorithm with Morrow mean stress correction (2):

$$\frac{\Delta\gamma_{max}}{2} + \frac{\Delta\varepsilon_n}{2} = 1.65\frac{\sigma_f' - \sigma_{mean}}{E}(2N)^b + 1.75\varepsilon_f'(2N)^c, \qquad (2)$$

where $\Delta\gamma_{max}$ is the maximum shear strain range, $\Delta\varepsilon_n$ is the normal strain range, σ_f' is the fatigue strength coefficient,

σ_{mean} is the mean normal stress, E is the Young's modulus, $\varepsilon_f^{'}$ is the fatigue ductility coefficient, b is the fatigue strength exponent, b is the fatigue ductility exponent, N is the fatigue life.

Fatigue life post-processing was performed using commercial durability analysis software Fe-Safe 2022. For each alternating bending moment, the location with the shortest predicted fatigue life at the threaded connection was identified as the hotspot, and this minimum value was recorded as the fatigue life corresponding to that bending moment.

Fatigue life was calculated for a range of bending moments up to 60 kft-lbf. Figure 10 depicts the example of the resulting data points, extracted from the FE model. A smooth curve fitted through these points yields the BM–N (bending moment vs number of cycles) curve. The predicted hotspot was located at the first thread root on the box (flow diverter) side. This finding is consistent with field failure observations.

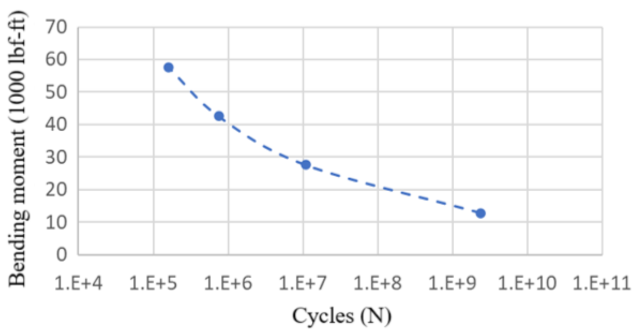

Figure 10. Typical fatigue curve for connector.

5. BENDING MOMENT CALCULATION

The workflow utilizes an in-house drilling simulator (DS) to estimate the bending moment on critical connectors under downhole loading conditions and wellbore contact constraints.

5.1. In-House Developed FE Simulator

Understanding the actual loading conditions of subsurface tubulars and maintaining their integrity in harsh downhole environments remains a significant challenge in the oil and gas industry. To address these challenges, an in-house FE-based simulator was developed to provide detailed insights into the mechanical behavior of drill strings under various operational conditions – insights that are crucial for implementing condition-based maintenance strategies and minimizing the risk of tool failure.

This advanced and versatile drilling simulation platform is built on a powerful 3D non-linear FE engine. The model can simulate both static and dynamic responses of the drill string, from the bit to the surface, while accounting for detailed tool dimensions – such as the motor's inner shaft and outer housing – as well as geometric constraints resulting from contact interactions between the wellbore and tubulars.

This comprehensive modeling capability enables accurate calculation of bending moments at critical locations within drilling motors, including both external and internal threaded connectors. The simulator has been extensively applied in various domains, including bit selection, drilling tool design, optimization of drilling parameters, post-job model validation, and failure analysis.

5.2. Technical Details and Model Validations

The simulator requires detailed input data, including the complete drill string configuration, tool dimensions, material properties, and wellbore trajectory. These inputs are essential for generating an accurate representation of the drill string and its interaction with the wellbore.

The simulator uses the finite element method to model the drill string. Figure 11 shows the schematic of a beam element, which serves as the fundamental building block of the 3D drill string model. Each beam element in the model has six degrees of freedom (DOFs): three translational and three rotational.

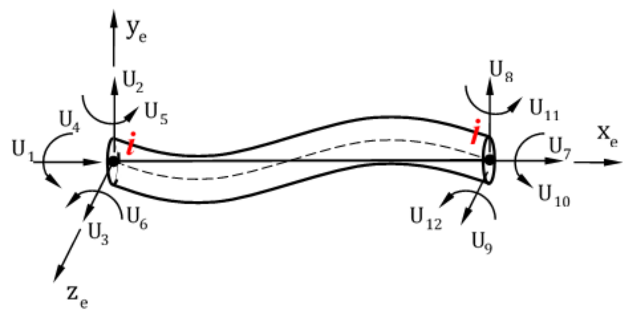

Figure 11. 3D beam element used in drilling tubular simulator.

The FEM formulation incorporates the nonlinear interaction between torsional and bending degrees of freedom. Combined with a robust implicit FEM solver, this enables accurate simulation of large deformations in the drill string under the constraints imposed by the wellbore.

The simulator is capable of modeling both static and dynamic loading conditions (Chen, Shen, and Chen, 2021). In the static simulation mode, the drill string is assumed to remain stationary within the wellbore. Appropriate boundary conditions are applied to represent downhole forces, including axial and torsional loads, as well as contact interactions between the drill string and the wellbore walls. Consistent with standard FEM procedures, the mechanical behavior of the drill string under static conditions is governed by the equilibrium equation (3):

$$[\mathbf{K}]\{\mathbf{U}\} = \{\mathbf{F}\}, \tag{3}$$

where [**K**] is elasticity stiffness matrices; {**U**} and {**F**} are displacement and external force vectors of the drill string.

The static equilibrium is solved iteratively using an implicit method. As a result, the deformed shape and the forces at each node of the beam elements can be determined using Equation 3. The bending moment – one of the internal forces within a beam element – is calculated by summing the product of the nodal displacements and the element's bending stiffness. At wellbore contact points, a static normal contact force and a shear force, equal to the Coulomb friction, are applied. The shear force acts in the direction opposite the rotation of the tubular (Figure 12). Additional modeling details for both static and dynamic loading scenarios can be found in Chen et al. (2021).

The simulator is particularly well-suited for modeling the conditions encountered during directional drilling operations in the oil and gas industry. It can simulate static deformation, wellbore contact forces, and bending moments experienced by the drill string and drilling tools under a variety of operational scenarios.

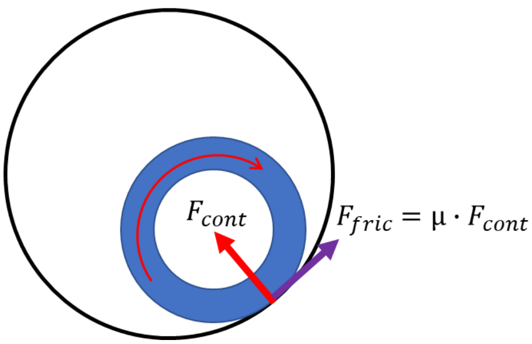

Figure 12. Contact normal and frictional forces in static drill string model.

Figure 13 presents the dynamic simulation results of the bending moment at a critical location in the drilling tool connection. The downhole drilling tool is subjected to severe whirling motion – a harmful lateral vibration of the tubular – which leads to elevated bending moments. The bending moment results (shown on the right-hand side of Fig. 12) illustrate the time history of dynamic bending moments. The X-axis represents the number of collar rotations. The results indicate that the bending moment oscillation frequency is significantly higher – approximately 14 times – than the collar rotation frequency under conditions of severe drilling dynamics.

Figure 14 presents the static bending moment simulation for a loading scenario in which the drill string is subjected to static forces caused by directional wellbore curvature. The top image in Fig. 14 shows the wellbore trajectory drilled by the drill string. A downhole strain gauge sensor was deployed in the drill string to measure the bending moment during this operation. The bottom chart in Figure 14 compares the simulated bending moment with the sensor measurements. A strong correlation is observed between the simulation results and the actual measurements, which is critical for validating the accuracy of the simulation model. Such validation is essential for building confidence in the simulator's predictive capability. Additional validation studies, including comparisons with classical analytical solutions and downhole sensor data, can be found in Chen, Yang, Chen, Yun, Shen, and Huang (2012).

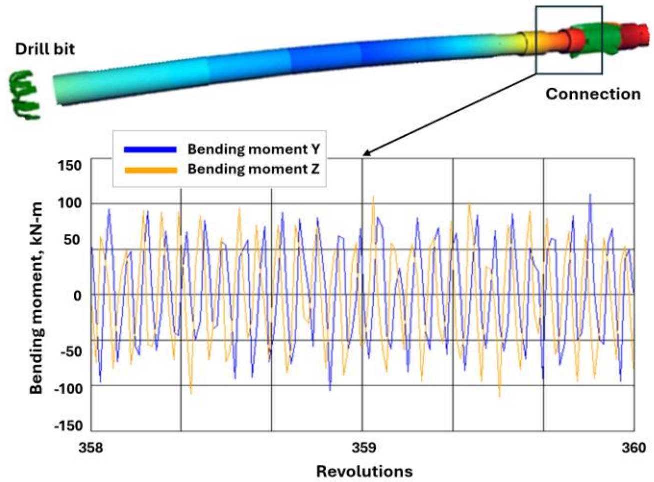

Figure 13. Dynamic bending moment simulation due to drill string whirling motion. Bending moments Y and Z are moments for the Y and Z axes perpendicular to the drill string.

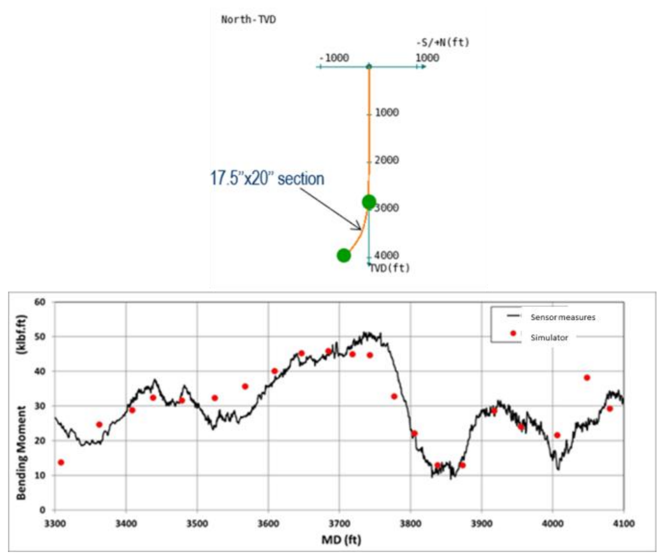

Figure 14. Static bending moment simulation of drill string within a directional wellbore.

5.3. Incorporation of the Simulator into the Real-Time Monitoring Pipeline

The simulator can be employed to perform real-time simulations, tracking the evolution of bending moments as drilling advances to greater depths along the wellbore. By continuously updating the model with live data, the simulator provides ongoing predictions of bending moments – crucial for monitoring and assessing the structural integrity of the drill string and for mitigating the risk of tubular bending fatigue failure.

Integrating modeling results from in-house drilling dynamic finite-element simulator into a real-time workflow for tubular bending fatigue computation and monitoring enables operators to make informed decisions that optimize drilling performance while enhancing the safety and reliability of operations. This comprehensive approach supports risk reduction related to bending fatigue and helps maintain the integrity of subsurface tubulars.

6. VALIDATION

BHA connectors are commonly reused across multiple drilling operations involving varying bottom-hole assembly configurations and wellbore trajectories before they reach the end of their service life or are decommissioned. To assess the precision of the proposed PHM algorithm, it is necessary to monitor a specific connector throughout its entire operational lifespan – from its initial deployment to final usage – by calculating the resource consumption per job and tracking the cumulative remaining useful life. For robust validation, both successful deployments (without failure) and unsuccessful ones (failure) should ideally be included. However, due to limited availability of failure-case data, the evaluation was performed exclusively on successful runs using historical drilling records.

6.1. Validation Based on Legacy Data

Drilling along a well trajectory characterized by low Dog-Leg Severity generally imposes minimal mechanical stress on BHA connectors, resulting in limited impact on their fatigue life (Belov & Chen, 2023). To illustrate this, consider a case involving the drilling of a 1,700-meter-long horizontal section, extending from 3,500 to 5,200 meters measured depth. The bottom-hole assembly used in this operation includes 7-inch mud motor connectors—specifically, the top sub, stator adapter (external connectors), and the internal connector between the drive shaft and flow diverter.

Due to the smooth and stable well path, marked by only minor variations in inclination and azimuth (as shown in Figure 15), the connectors experience relatively low mechanical loads. These slight directional changes result in minimal structural bending, reducing the accumulation of stress and strain within the components.

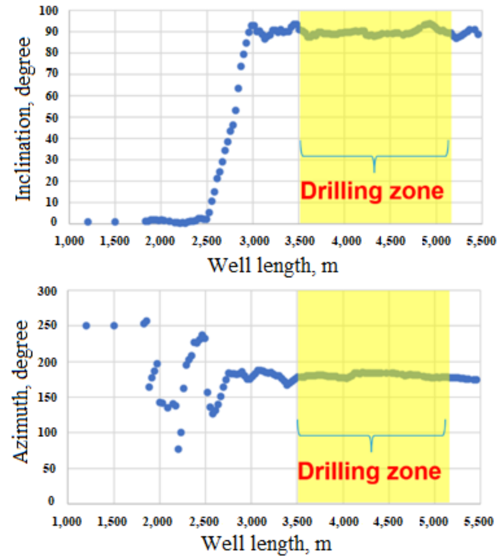

Figure 15. Inclination (top) and azimuth (bottom) profiles for a well trajectory section characterized by low Dog-Leg Severity.

Figure 16 shows the calculated bending moment as a function of measured depth for two representative BHA segments near the top sub and stator adapter (the last one is close to the internal connector as well). In this scenario, the average bending moment for each component is approximately 0.7 thousand lbf-ft, with a few localized peaks reaching up to 3 thousand lbf-ft.

The consistently low bending moments observed during this drilling phase led to only minor fatigue damage in the connectors. The estimated reduction in fatigue life is 3.1% for the top sub, 2.4% for the stator adapter, and approximately 8.3% for the internal connector between the drive shaft and flow diverter. The higher fatigue consumption in the internal connector is attributed to its lower structural durability and higher rotational loading – since mud motor output rotation must be considered due to the specific BHA design. These results align with theoretical expectations for low-DLS drilling scenarios and demonstrate the limited degradation experienced by BHA components in such conditions.

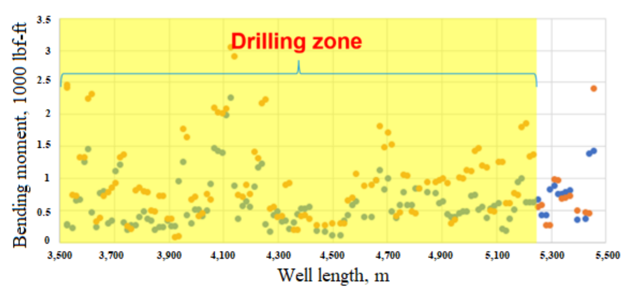

Figure 16. Bending moment versus measured depth for the low-DLS section of the well trajectory, with blue dots representing values at the top sub position and orange dots representing values at the stator adapter position.

In contrast, well trajectories with high DLS impose significantly greater mechanical stress on the same connectors, leading to more substantial fatigue accumulation (Belov & Chen, 2023). For instance, consider drilling a 1,700-meter-long transitional section – from vertical to horizontal – extending from 2,500 to 4,200 meters measured depth. This interval features a continuous increase in inclination from 0 to 90 degrees. The BHA configuration remains the same, utilizing 7-inch lower-end connectors.

As shown in Figure 17, the changes in inclination and azimuth are much more pronounced than in the previous example, resulting in aggressive wellbore curvature.

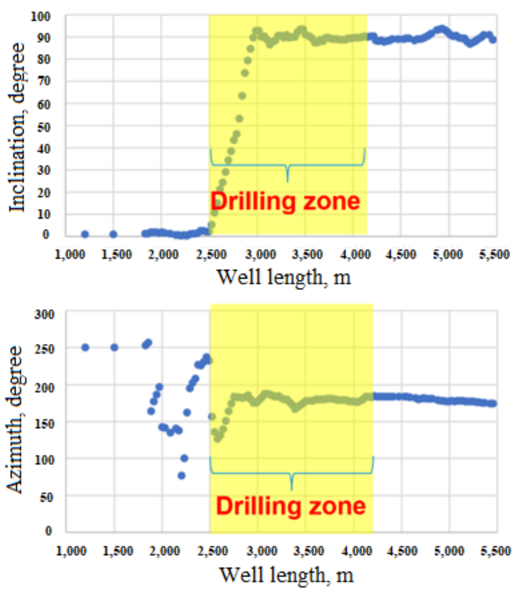

Figure 17. Inclination (top) and azimuth (bottom) profiles for a well trajectory section characterized by high Dog-Leg Severity.

Figure 18 presents the corresponding calculated bending moments along the well trajectory for both the top sub and stator adapter, clearly indicating significantly higher values during the curved section compared to typical vertical or lateral intervals.

This intensified loading environment results in a marked reduction in the RUL of the connectors. By the end of the drilling operation, the RUL of the top sub had dropped to 86%, the stator adapter to 92.5%, and the internal connector to 73.2%. These findings highlight the critical importance of accounting for wellbore curvature when assessing fatigue life and emphasize the value of predictive PHM algorithms in safeguarding the structural integrity of BHA components under challenging drilling conditions.

Running the developed algorithm on legacy data enabled the calibration of safety factors for the model and supported the development of the final workflow for integration with real-time data sources through the internal health monitoring framework. This process also helped define initial RUL thresholds, which have been associated with failure risk alerts using a color-coded system (e.g., green, yellow, red).

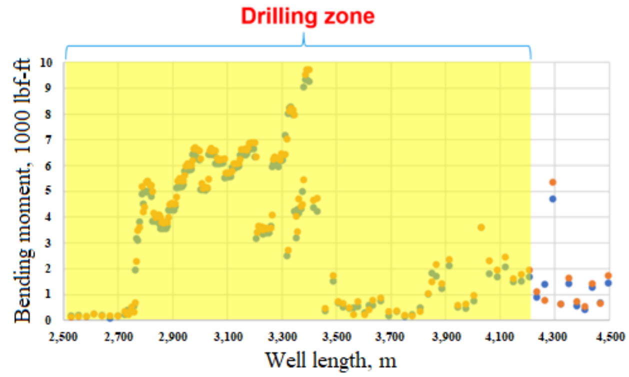

Figure 18. Bending moment versus measured depth for the high-DLS section of the well trajectory, with blue dots representing values at the top sub position and orange dots representing values at the stator adapter position.

6.2. Validation Based on Field Test

Between 2023 and 2024, several field trials were conducted to evaluate the performance of the PHM model designed for critical BHA connections, with a particular focus on external connectors such as the top sub and stator adapter. The results confirmed that both the model and the accompanying workflow are effective in identifying fatigue-related issues in these components.

This paper, however, shifts attention to the internal connector – specifically, the connection between the drive shaft and the flow diverter. From a fatigue standpoint, this internal component is notably more prone to damage than the external connectors. Its increased vulnerability is attributed to both its structural design and operational characteristics. While external connectors rotate at the speed of the surface drive system, the internal connector is subjected to significantly higher rotational speeds, as it operates at the output rate of the mud motor's power section during drilling. This results in more intense mechanical loading and necessitates focused monitoring.

Initial monitoring of the internal connector was conducted passively, following voluntary recommendations to observe but not act on alerts during early-stage field testing. In two documented cases where the drive shaft–flow diverter connector experienced fatigue-related failure, the PHM system successfully issued early warnings indicating a high structural failure risk.

One such case is detailed below. During the drilling of a vertical section at a depth of approximately 2,380 meters, a sudden pressure drop of 150 psi was recorded, prompting further attention. Despite attempts to resume drilling, no progress was made even with weight on bit (WOB) applied. The BHA was picked up for inspection, and a second attempt to resume drilling yielded the same result – lack of penetration.

No erratic torque or prior abnormal pressure readings were noted, making the situation unexpected. Upon further troubleshooting, it became evident that the power section was unable to rotate the BHA at sufficient speed. A decision was made to pull the tool from the hole due to suspected transmission failure. After retrieval, inspection revealed that the flow diverter had twisted off from the box connection with the drive shaft (Figure 19), confirming a mechanical failure at the internal connector.

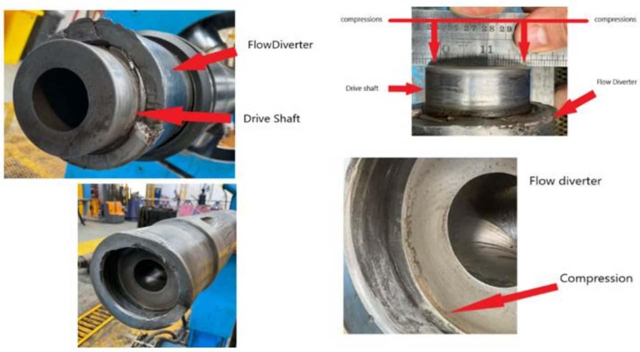

Figure 19. Damaged connector.

Laboratory examination of the fractured flow diverter revealed characteristics consistent with a low-load, high-frequency fatigue failure, evidenced by distinct fatigue markings. The connector in question had been continuously monitored using the developed PHM algorithm throughout its deployment across four consecutive drilling operations. The estimated RUL at the end of each drilling job is summarized in Table 1.

The results indicate that the RUL limit was exceeded during "Run 3", as the calculated value fell below zero. At this stage, the flow diverter—identified as the most fatigue-sensitive component of the connector—should have been retired and replaced with a new part. Unfortunately, the component remained in service and was used in a subsequent drilling job, which, despite having a relatively low DLS for well trajectory, resulted in connector failure. This incident clearly demonstrated the value of the proposed PHM solution and contributed to its adoption as a standard part of routine drilling monitoring.

Table 1. Summary of the PHM results.

Job/Run	Drilled metrage, m	Pumping time	Spent resource, %	Accumulated RUL, %
Run 1	2114.9	97 h 51 min	3.81	96.19
Run 2	46.9	19h 40 min	16.42	79.77
Run 3	2981.4	108 h 36 min	87.23	-7.46
Run 4	1796.7	131 h 24 min	15.09	-22.55

Subsequent field experience confirmed that setting a 30% RUL threshold provides a reliable safety margin for continued operation. Drilling should be suspended if the RUL for this internal connector falls below that level, and the component should be replaced before proceeding.

The field trials also provided practical insight into the necessary frequency of RUL updates during operations. It was shown that running the algorithm on new real-time data every minute is unnecessary. Given the physical characteristics of fatigue accumulation, a 30-minute update interval is sufficient for effective monitoring of the internal connector's condition.

In summary, the field tests demonstrated that applying the PHM algorithm after each run provides accurate and timely RUL estimates. This enables early identification of at-risk components and supports proactive replacement decisions, ultimately improving operational safety and reliability.

7. CONCLUSION

This paper presents a significant advancement in the real-time health monitoring of bottom-hole assembly connectors by integrating physics-based fatigue modeling with data-driven methods. The focus is on one of the most fatigue-prone components – the connection between the flow diverter and the drive shaft behind the mud motor power section – where failures can result in substantial non-productive time and increased operational risk.

The developed PHM system offers a hybrid solution that combines finite element–derived S–N curves and a physics-based simulator with a real-time, data-driven software framework to assess fatigue damage continuously. By ingesting both surface and downhole parameters – either directly measured or estimated through surrogate models – the system reliably estimates bending moments and rotational speeds, even when MWD data is unavailable. This ensures robust fatigue tracking across a wide range of drilling conditions.

A key strength of the approach lies in its compatibility with serialized connector data and historical job records, enabling comprehensive tracking of each component's fatigue history over its operational lifetime. Validation results demonstrate a strong correlation between predicted fatigue damage and actual connector failures, reinforcing the model's accuracy and practical value. Field trials – including both successful deployments and documented failures – have shown the system's capability to generate early warnings and support timely replacement decisions, particularly for internal connectors exposed to high rotational loads.

In addition, the paper discusses the real-world deployment of this PHM system within a commercial field platform. Real-time insights from the system have empowered field personnel to make proactive decisions regarding connector integrity, leading to improved reliability and extended service life of critical BHA components. Field experience has also helped optimize RUL threshold settings and update real-time refreshing frequencies, striking a balance between computational efficiency and diagnostic effectiveness.

In conclusion, the solution provides a reliable, field-validated framework for minimizing fatigue-induced failures in BHA connectors. By enabling real-time risk assessment and decision-making, it enhances drilling safety, reduces downtime, and lays the foundation for future digital PHM applications in well construction.

ACKNOWLEDGEMENT

This work was made possible through collective support, collaboration, and exchange of ideas across the entire organization. While there are too many individuals to acknowledge individually, special recognition is due to Kent Phillips, whose initial vision and business justification were instrumental in launching this effort. Significant contributions during the early development of the FEA-based fatigue curve estimation were made by Kinzie Juergens Dean and Josh Scribbins. Additionally, Eimund Liland and Asim Malik provided essential guidance and insights that greatly supported the progress of the project.

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BIOGRAPHIES

Dmitry Belov received his Ph.D. in Mechanical Engineering with a focus on applied mechanics and computational modeling from St. Petersburg State Polytechnic University. He joined SLB in 2008 as a Research Scientist and has since held several technical positions within the company, including Physicist, Modeling & Simulation Engineer, and Data Scientist. Currently, Dmitry serves as a Principal Data Scientist in Houston, TX, leading the development of advanced drilling technologies for the oil and gas industry. His work centers on predictive analytics, digital twins, and machine-learning solutions for Prognostics and Health Management (PHM) applications, with an emphasis on improving asset reliability, enabling condition-based maintenance, and optimizing the performance of downhole tools and drilling systems. His technical expertise spans numerical simulation, signal processing, algorithm development, and data-driven optimization.

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Jennifer Gilliam was born in Kentucky, USA. She graduated with a bachelor's degree in chemical engineering from North Carolina State University in Raleigh, North Carolina, USA. Jennifer joined SLB in 2011 as a Field Engineer delivering Measurement While Drilling, Logging While Drilling and Directional Drilling services to offshore clients in the Gulf of Mexico and offshore Canada. Since 2018 she has been in her current position as Service Quality Engineer (SQE) for Positive Displacement Motors (PDM). Her role focuses on monitoring and improvement of performance, reliability and/or operational cost of PDMs. In this role she is responsible for testing and worldwide support of PHM for PDMs.

Yaou Wang received his doctorate in Mechanical Engineering from The Ohio State University. Following that, he worked in the automobile industry before transitioning to the oil and gas sector. To date, he has accumulated over ten years of experience in computer-aided design and analysis, as well as in design and process optimization using statistical methods. He is currently a Senior Modeling and Simulation Engineer at SLB, the world's leading oilfield services provider. His responsibilities include design analysis and optimization of drilling equipment, along with the development of new simulation methods and automated procedures.