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Quantifying drilling vibration challenges

Vibration risk index offers tool for preventing drillstring failure

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Recent discoveries in Brazil ultra-deepwaters and confirmation of its huge potential have started an unprecedented exploratory campaign in water depths exceeding 2,000 m (6,500 ft).

Many deep vertical exploration wells are being drilled. However, to varying degrees, all these wells share the common threat of drillstring failures resulting from extreme drilling dynamics events in vertical hole sections.

Of these challenges, one main contributor to nonproductive time is drillstring integrity failure related to challenging drilling mechanics, particularly when drilling the 17½-in. or bigger sections. Failures are most common after the soft sediments have been drilled and more competent and intercalated formations are encountered.

These drillstring integrity failures result in time-consuming and costly fishing or side tracking operations, and the potential loss of downhole equipment. These challenges are particularly high in exploration areas such as deepwater Brazil, where there are often few nearby offset wells and operations can be a long way from supply bases.

Vibration-related failures

Vibration-related failures are a frequent occurrence. Schlumberger has measured drillstring vibrations in real time since the beginning of mud-pulse telemetry, initially focusing on tool reliability. This experience has consolidated an understanding of measured vibrations and how they correlate with drillstring damage.

Guides have been developed for reacting to high instantaneous vibration levels (Figure 1). Experience indicates that most normal drilling operations occur within the green and yellow zones, and also that significant damage occurs when lateral vibrations increase above 3 G Root Mean Square (RMS). However, even with the use of real-time downhole sensors and drilling optimization teams implementing mitigation actions, vibrations have often not been cured, and continuous destructive vibrations have been witnessed until a failure occurred.

Sometimes, mitigation of poor drilling mechanics is only achievable by a significant re-design of the drilling system to obtain a stable drillstring and bit combination. This is clearly not a real-time solution, and the decision to drill ahead is often made due to the lack of an acceptable justification to do otherwise.

Vibration analysis

Many deepwater drilling runs have been closely studied in an attempt to better understand the relationships between shocks and vibrations versus integrity failures. It is evident that a more robust set of criteria for a more reliable risk indicator—based on downhole vibration measurements—is required to trigger a process to pull the string out of the hole in time to prevent costly integrity failures. In pursuit of this objective, Schlumberger has performed an analysis of vibration data from 16 bit runs from eight deepwater exploration wells offshore Brazil. The bit-run analysis was performed during a two-year period. The runs shared similar characteristics in terms of bottomhole assembly (BHA) design and section size; all the sample bit runs used 9½-in. collars.

It was evident that drilling mechanics conditions are complex and vary significantly from one run to another, as observed in the many surface and downhole parameters available for analysis. Some of the sample runs encountered severe drilling dynamics regimes and ended with string integrity failures.

Although it proved impossible to identify a single parameter that described downhole mechanics accurately, the analysis of measurements of lateral vibrations, and in particular the calculation of cumulative vibration intensity, were found to show direct correlation with the occurrence of drilling mechanics failures. This finding potentially provides the basis for quantification of a risk index that will help predict and mitigate catastrophic drillstring failure.

Cumulative vibration intensity

The field of seismological design, related to the effects of earthquakes, has developed testing techniques using vibrations that impose increasing dynamic demands into structures in order to test the extent of damage and define endurance limits for seismic-resistant buildings and other constructions. The deepwater drilling study implemented a similar concept to calculate, based on downhole vibration data, the cumulative dynamic demand imposed on the drilling assembly for the duration of a bit run.

The results were then compared to actual drillstring failure events to determine any relationship. The ultimate goal was to determine an endurance limit for drilling assemblies that could be used to prevent catastrophic failures related to destructive drilling dynamics.

RMS lateral vibration measurements, provided by a multi-axis vibration cartridge in the BHA, were observed to have the most influence in describing the severity of drilling dynamics. Using this measurement, a Vibration Intensity parameter $V$ is defined, with units $g$'s, based on a time history analysis: $V = \int a^2(t) \, dt \equiv \int Viblat^2(t) \, dt$. This calculation of $V$ is based on the same technique used when measuring ground motions from an earthquake, in which accelerograms are recorded and then an integral of the square of the measured acceleration is used to calculate the intensity of the accelerogram for the duration of the strong motion period. This is the period at which the contribution to the total value is significant over the length of the seismic movement.

Calculating the integral of the squared measured lateral vibrations (in g) over the duration of a bit run represents the intensity of the acceleration, or vibrations, imposed on the drilling assembly; in other words, the destructive energy of the bit run imposed on the assembly.
Figure 2 shows examples of vibration data recorded in real-time while drilling; the red line shows the equivalent $V_i$. Using the described methodology, this parameter can be calculated in real-time and used to do a quick assessment of the level of cumulative drilling dynamics severity imposed on the BHA at any point in the run. This is not possible using the RMS lateral vibrations data alone, and using this for comparison between bit runs can become subjective.

In the accompanying comparison of RMS vibration measurements (blue spots) and $V_i$ (red line) for two of the sample bit runs in Figure 2, the lower panel shows peaks in lateral vibrations between many quiet periods. The top panel shows consistently strong vibrations, although without the high peaks.

The result is that, by the end of the run, $V_i$ for the top panel is almost twice that of the other sample, representing a higher risk of failure. This comparison highlights the value of the $V_i$ parameter in identifying risk at any time during a bit run, while RMS lateral vibration behavior can appear similar or lead to an erroneous interpretation. $V_i$ provides a snapshot of the current cumulative vibration risk of the run, and provides a comparative indicator for the implementation of optimization strategies.

Figure 3 shows the cumulative value of $V_i$ at the end of each of the 16 sampled bit runs. The columns in red represent runs that ended in a catastrophic event in which vibration was either a significant contributing factor or the root cause of the failure. A quick assessment of these results clearly shows that all the runs with cumulative vibration intensity over 1 million $g^2.s$ ended with a catastrophic failure. This was a significant

Figure 2. Lateral vibration and vibration intensity ($V_i$) for two bit runs

Figure 3. $V_i$ and $V_{rate}$ for all sample bit runs

Note: Despite peaks of high lateral vibrations, the lower panel has lower cumulative vibration intensity.

Note: Red columns indicate samples with vibration-related failures.
step towards the objective of defining a safe endurance factor for the drilling assembly based on vibration intensity.

**Vibration risk factor**

Stopping drilling when $V_i$ exceeded 1 million g$^2$.s would have prevented three out of the five catastrophic drilling dynamic failures in the 16 bit-run study. Another observation was that some of the runs that achieved significant $V_i$ but did not experience failures were very long runs that accumulated high ultimate $V_i$ at a slow rate. An example is Sample-2, which accumulated a $V_i$ of 654,000 g$^2$.s in approximately 200 operating hours, during which time it drilled approximately 1,000 m (3,280 ft).

By contrast, Sample-7 reached 738,000 g$^2$.s (13% higher) in just 70 hours. Comparisons such as this suggested investigating the value of an additional risk indication parameter – the vibration intensity rate ($V_{ir}$). This was computed by dividing the total vibration intensity for the bit run by the number of active hours – defined as openhole time including drilling, reaming, washing, and tripping operations.

The lower panel of Figure 3 shows $V_{ir}$, expressed in g$^2$.s/h, for the 16 sample runs. The four samples with the highest $V_{ir}$ represent all but one of the five catastrophic failures. Having observed that both $V_i$ and $V_{ir}$ had a clear effect on vibration-related risk in the samples studied, a risk factor was calculated that was the multiple of the two values with equal weight, i.e. $V_i \times V_{ir}$.

Sample-2 was a bit-run that achieved the normal lifespan expectation for the drilling assembly (200 hours) and experienced active drilling mechanics within what is normally expected for a drilling assembly to endure. Sample-2 consistently experienced average lateral vibration levels of 1.5 to 2 g RMS, with a significant number of short intervals in the region of 10 to 15 g RMS. This bit run would be considered medium risk in terms of vibration. For easier comparison, the computed risk factors for all 16 samples were normalized to the factor for Sample-2, so, the reference for base risk (1) is:

$$V_{risk-ref} = V_{ref} \times V_{rate-ref}, \quad \text{where} \quad V_{ref} = 654,000 \text{ g}^2.\text{s} \quad \text{and} \quad V_{rate-ref} = 3,270 \text{ g}^2.\text{s}/\text{h}.$$

For all runs the vibration risk index is calculated as:

$$V_{risk} = V_i \times V_{ir} / V_{risk-ref}$$

**Results and conclusions**

Figure 4 shows a consolidation of the vibration time records and the computed normalized risk index ($V_{risk}$) for the 16 sample bit runs. While cumulative vibration intensity ($V_i$) provides a snapshot indicator of the amount of vibrations an assembly has suffered up to any point of a, the incorporation of vibration intensity rate ($V_{ir}$) provides an index ($V_{risk}$) that correlates well with known outcomes of the sampled data.

This calculation can be performed during drilling and updated in real time to deliver a simple quantified index that can be used to improve operational procedures and decisions. Only one of the five samples that actually ended in drillstring integrity failure (Sample-12) had a risk index below three. This level of risk index is provisionally proposed as an operational limit at which mitigation should be mandatory, and action should be triggered to prevent a catastrophic drillstring failure.

In addition to analyzing vibration statistics from more bit runs, several other factors need to be considered. This study analyzed data from similar BHA designs with 9½-in. collars, and risk levels may vary with changing parameters such as tool size, connections, and mechanical strengths.

While more work is required, the authors believe that the described methodology to develop a vibration risk index is robust. Of 16 bit runs analyzed, four out of five failures experienced would have been prevented with a decision triggered when the proposed risk index level was reached. The drillstring failure in Sample-12 can be tracked to a root cause other than vibrations, which were only a secondary contributing factor.

Although the results and proposed operational limits are based on limited statistics, recent additional studies indicate that the methodology is robust for other bit sizes and the same scale can be assumed valid as a starting point in other environments.

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**Figure 4. Vibration time history (top), $V_i$ and $V_{risk}$ for all sample bit runs**

![Vibration time history](image-url)