FAILURE ANALYSIS AND GENERALIZATION OF LOAD INSTABILITY IN MECHANIZED BHA HANDLING SYSTEMS FOR OFFSHORE DRILLING

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Abstract: *Mechanized pipe handling systems improve offshore drilling safety but introduce configuration-dependent risks. This paper analyzes a near-miss incident involving loss of control of a Bottom Hole Assembly (BHA) handled with a Hydraracker system. The study combines incident reconstruction, mechanical analysis, numerical validation, safety margin evaluation, and uncertainty quantification. Results show that load asymmetry, absence of stabilizing constraints, and lack of procedural control led to deterministic failure. The findings emphasize the need for configuration validation and safety margin assessment in mechanized operations*.

Keywords Offshore drilling, Hydraracker, BHA, load stability, uncertainty quantification.

1. INTRODUCTION

This paper analyzes a real handling failure and demonstrates that the outcome was mechanically predictable. Furthermore, it extends the analysis into a generalized framework applicable to mechanized handling systems.

2. LITERATURE REVIEW

Mechanized pipe handling systems have significantly reduced manual handling risks in offshore drilling; however, recent studies indicate that automation introduces new categories of hazards related to system configuration, control logic, and human-machine interaction [4],[5],[13].

Recent research in offshore safety highlights that dropped objects and loss-of-control events remain among the leading causes of high-potential incidents, often linked to inadequate load stability assessment and insufficient barrier integrity [7],[8],[14].

Studies emphasize that non-standard operational configurations represent a critical gap in existing procedural frameworks. Barrier-based safety models have evolved from linear causality approaches to systemic interpretations, where failures emerge from the interaction of degraded safeguards rather than a single root cause [6],[11],[15].

This perspective aligns with resilience engineering principles, where system performance variability can lead to unexpected outcomes. In parallel, lifting and handling engineering literature defines stability through equilibrium conditions and safety margins, requiring that resisting forces exceed applied loads under all operating conditions.

However, in offshore practice, these principles are not always explicitly verified during mechanized handling operations [3],[10].

The mechanical analysis is based on classical equilibrium principles commonly applied in lifting and offshore engineering systems [10].

3. METHODOLOGY

The methodological approach adopted in this study combines deterministic mechanical modeling with safety engineering principles. This approach aligns with structured risk-informed engineering methodologies used in safety-critical offshore systems [9], [11].

4. CASE STUDY DESCRIPTION

The operation involved laying down a 9.5-inch BHA using the Hydraracker. Key conditions:

- Only intermediate arm engaged
- Guide arms not effectively used
- Asymmetric load distribution

The BHA detached during positioning and impacted the derrick structure.

5. MECHANICAL ANALYSIS

Center of Gravity

$$x_{CoG} = \frac{\sum m_i x_i}{\sum m_i} \tag{1}$$

The CoG was significantly below the gripping point, creating instability.

Overturning Moment is:

$$M_{net} = W_{below} \cdot d_{below} - W_{above} \cdot d_{above} \tag{2}$$

As shown in (2), load asymmetry increases the overturning moment. Stability Condition is:

$$F_g \cdot r \geq M_{net} \tag{3}$$

Failure occurs when:

$$F_g \cdot r < M_{net} \tag{4}$$

6. NUMERICAL VALIDATION

The overturning moment derived in (2) is used as the basis for numerical validation.

6.1 Input Data

$W_{below} = 8\,\mathrm{t}$, $d_{below} = 25\,\mathrm{m}$, $W_{above} = 1.5\,\mathrm{t}$, $d_{above} = 10\,\mathrm{m}$

6.2 Calculation

$$M_{net} = (8 \times 25) - (1.5 \times 10) \rightarrow M_{net} \approx 1815\,\mathrm{kN \cdot m} \tag{5}$$

6.3 Interpretation

The calculated moment significantly exceeds stable handling conditions, confirming mechanical instability.

6.4 Uncertainty and Assumptions

The calculation is based on simplified assumptions. Uncertainties includes:

- Variability in mass distribution
- Approximation of distances
- Dynamic effects (e.g., sudden stopping or minor movement)

Despite these, the magnitude of M_{net}confirms robustness of the failure mechanism.

7. SAFETY MARGIN ANALYSIS (*SM*)

$$SM = \frac{F_g \cdot r}{M_{net}} \tag{6}$$

Stable operation requires: $SM \geq 1$

This formulation is consistent with established lifting stability and offshore risk evaluation methodologies [10], [11].

8. UNCERTAINTY QUANTIFICATION

Scope and approach evaluation of the overturning moment M_{net} depends on measured or estimated quantities, including weights and distances from the gripping point.These quantities are subject to uncertainty due to operational variability and measurement limitations.
A first-order uncertainty propagation method is applied to estimate the uncertainty in M_{net}.
The following variables are considered uncertain parameters:

W_{below}, W_{above}: mass estimates and d_{below}, d_{above}: geometric distances

8.1 Propagation of Uncertainty

Each variable is associated with an uncertainty, are: W_below± δW_below, W_above± δW_above and d_below± δd_below, d_above± δd_above. Given:

$$M_{net} = W_{below} \cdot d_{below} - W_{above} \cdot d_{above} \quad (7)$$

The combined uncertainty δM_{net} is approximated using first-order Taylor expansion:

$$\delta M_{net} = \sqrt{(d_{below} \cdot \delta W_{below})^2 + (W_{below} \cdot \delta d_{below})^2 + (d_{above} \cdot \delta W_{above})^2 + (W_{above} \cdot \delta d_{above})^2} \quad (8)$$

Illustrative estimation assuming conservative uncertainties: δW ≈ ±10% and δd ≈ ±5%
The propagated uncertainty remains significantly smaller than the magnitude of M_{net}.

8.2 Impact on Safety Margin

The safety margin becomes:

$$SM = \frac{F_g \cdot r}{M_{net} \pm \delta M_{net}} \quad (9)$$

Given that M_{net} is substantially large, even when reduced by uncertainty bounds, results $SM < 1$ is valid.

8.3 Interpretation

The analysis demonstrates that:

- The instability conclusion is not sensitive to reasonable parameter uncertainty
- The failure condition persists across the uncertainty range

This confirms that the incident outcome is robust and not dependent on precise parameter estimation. The system operated outside safe limits under all plausible conditions.

9. GENERALIZED STABILITY FRAMEWORK

$$SM = \frac{F_g \cdot r}{\sum(W_i \cdot d_i)} \quad (10)$$

A stable configuration requires $SM \geq 1$.
The framework identifies three independent dimensions influencing stability:

- Mechanical: load distribution and geometry
- Configuration: gripping and stabilization mechanisms
- Operational: procedures, monitoring, and communication

Failure occurs when degradation in one or more dimensions reduces the safety margin below unity.

10. DISCUSSION

The results demonstrate that the failure mechanism is governed by fundamental static equilibrium principles, independent of system complexity.The combination of load asymmetry and insufficient stabilization created a condition where the overturning moment exceeded the available resisting capacity. This condition is deterministic and predictable.

From an engineering perspective, the key implication is that mechanized systems require explicit validation of load configurations. Reliance on routine classification or operator experience is insufficient when handling non-standard assemblies.

The integration of mechanical analysis with barrier evaluation is consistent with modern risk-based approaches in offshore safety engineering [7], [11], [14].

The observed interaction between system configuration and human decision-making aligns with findings in human reliability and situation awareness studies [5], [13].

The proposed framework contributes to bridging the gap between deterministic mechanical analysis and probabilistic risk-based safety approaches in offshore engineering.

11. ALIGNMENT WITH INDUSTRY STANDARDS

The findings align with:

- API RP 54 – Safe Handling Within Operational Limits
- ISO 17776 – Hazard Identification for Non-Routine Tasks
- ISO 12100 – Consideration of Abnormal Operating Conditions

The incident represents deviation from these principles.

These findings are consistent with established offshore risk assessment methodologies and safety management frameworks [9], [14].

12. LIMITATIONS

The study is based on a single incident and a simplified mechanical representation of the system. While the model captures the dominant physical behavior, it does not account for dynamic effects such as impact loading or transient oscillations.

Additionally, the absence of detailed manufacturer data limits the ability to quantify the exact resisting capacity of the gripping system.

Future work should include:- Experimental validation or simulation-based analysis; - Inclusion of dynamic effects; - Application of the framework to multiple case studies.

The absence of time-dependent or dynamic modeling represents a limitation in capturing transient instability effects.

13. CONCLUSION

This study demonstrates that load instability in mechanized BHA handling can be explained through fundamental equilibrium principles and safety margin analysis.

The integration of mechanical modeling, uncertainty quantification, and barrier analysis provides a comprehensive interpretation of the incident and its underlying causes.

The proposed generalized stability framework extends the applicability of the findings beyond the specific case, offering a structured approach for evaluating mechanized handling safety. The results highlight that failures in automated systems are not solely due to mechanical limitations but emerge from the interaction between system configuration, operational conditions, and degraded safety barriers.

This work contributes to bridging the gap between theoretical stability analysis and practical offshore operations. While the model captures the dominant physical behavior, it does not account for dynamic effects such as impact loading or transient oscillations.

These results highlight potential benefits rather than guaranteed field outcomes. As adoption increases, hybrid models—AI support with human oversight—will likely dominate in the near term. Field validation is required to confirm actual performance under diverse operational conditions. Over time, the industry can expect a gradual transition toward fully autonomous drilling rigs, delivering safer, more sustainable, and more cost-effective well construction. The results highlight main benefits of AI-integrated failure analisys:

- Improved Efficiency: Higher and more stable ROP reduces drilling cost
- Enhanced Safety: Faster response to anomalies minimizes well control risks
- Consistency: Standardized performance independent of crew skill level
- Cybersecurity risks in automated rigs
- Regulatory and certification hurdles.

Human acceptance consist in transitioning from operator-driven to AI-driven decisions requires trust. A practical failure analysis and generalization of load instability roadmap involves hybrid automation: human-in-the-loop AI systems today, moving gradually toward full autonomy as technology and regulations mature.

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