BENEFITS OF MODERN INSTRUMENTATION FOR HULL MOTIONS AND SEASTATES DURING JACKUP RIG MOVES

James N. Brekke

Brekke Offshore Consulting, LLC

Thomas L. Johnson

BMT Scientific Marine Services Inc.

Abstract

This paper describes how modern instrumentation systems benefit jackup operations moving on and off location, particularly in sea conditions that are persistent or borderline. Such instrumentation leads to less time spent waiting on weather, reduced exposure to risk of incidents, and fewer commercial disputes between operators and contractors.

The capability of a jackup to move on and off location safely and efficiently is established on site by gathering knowledge of the prevailing seas and jackup hull motions. On-site observations drive the decision-making for moving the jackup. Most of the world's jackups still rely on old-fashioned devices and processes in making these observations, and these can have significant shortcomings. "Level indicators" on the hull use a bubble in a tube of fluid, whose primary purpose is to measure the static tilt of the hull. When used to measure angular motions, readings from these devices are contaminated by inertial effects. To estimate the prevailing seastate, trained crew members watch the ocean surface elevation rising and falling on a fixed reference point on the jackup. From this, they then extrapolate the significant wave height and zero-crossing period; however, this process falls short of accurately gathering many other seastate parameters such as dominant wave period, swell content, and wave direction.

The use of modern instrumentation in an operational advisory system has the potential to make the jackup installation safer and more efficient. Accelerometers mounted on the hull provide measurements of lateral and angular hull motions, and these can be used to estimate spudcan motions. This real-time knowledge is useful on site to identify spudcan impact concerns when moving on location. During leg extraction operations with the hull in the water, lateral motion measurements in real time are useful for understanding whether motions experienced by the hull are tolerable. Finally, prior to jacking down, downward-looking dynamic airgap measurements provide accurate information regarding the actual seastate so that informed decisions may be made whether the hull should be jacked down into the water or not. When compared to the observations being made on most jackups today, an approach that employs modern instrumentation provides a step change in identifying weather windows, identifying unexpected hazards, and allowing more clarity for an operator and contractor to agree on when it is safe to proceed.

Key Words: Instrumentation, Jackup Moving On Location, Jackup Moving Off Location, Operational Advisory, Spudcan, Seastate, Fixity

Introduction

Certain types of jackup designs have evolved with relatively slender legs to reduce wave loading on the jackup during the elevated condition. Although jackup rig move operations have generally been restricted to relatively mild conditions, jackups with slender legs have been even more restricted.

Operational limits have been defined to avoid incidents during moves on or off location. These limits guide the operations at relevant stages by helping answer the following questions:

- Is the weather too severe to put the spudcans down on the seabed as the jackup moves onto a location?

- Is the weather too severe to lower the hull into the water as the jackup prepares to move off location?

- Should the hull be jacked up out of the water due to forecasted severe weather when it is in the middle of a time-consuming leg extraction operation?

At each of the stages above, the jackup operation is exposed to the following risks:

- If the decision is to wait on weather, is the non-productive time warranted (too conservative)?

- If the decision is to proceed, will the jackup have an incident (too aggressive)?

- Whatever the decision, are the contractor and operator fully in agreement?

The consequences of an incorrect decision are as follows:

- Waiting on Weather: The operator suffers a needless loss of dayrate and spread costs; and the contractor loses in the long-term due to the operator's reduced appetite for the long-term viability of the drilling campaign.

- Incident Occurs: The contractor incurs the substantial cost of an "unplanned" repair project, loss of dayrate, loss of reputation for safety and predictability of service, potential loss of the current contract, and a delay jeopardizing the next contract. The operator incurs a delay at the present location and at a potential future location.

- Disputes between operators and contractors: The business relationship between the operator and contractor suffers and, worse yet, a legal dispute follows.

Present Industry Efforts

For several years the ISO 19905-4 Jackup Committee has been active in developing a standard to address Jackup Emplacement and Removal at a Site (i.e., jackup moves on and off location). In its present form, this draft ISO standard is intentionally broad, but it includes discussions of the engineering, planning, and operational support that relate to the operational decision-making and monitoring (field measurements) that are the subject of this paper.

Specific to jackup monitoring, in Reference 1 the American Bureau of Shipping (ABS) has "Guidance Notes on Self-Elevating Unit Motions Monitoring" (Confidential, available via NDA).

Relevant Offshore Measurements

The offshore industry has conducted jackup field measurements over the years for the primary purpose of validating/calibrating analysis methods in the industry standards (see examples in References 2, 3, and 4). However, measurements applied to an "operational advisory" for jackup rig move operations have not been done extensively. With the availability of modern instrumentation and interpretive advisory software, it is arguably time to start using these operational tools that enhance safety and efficiency. This section discusses some of the ways field measurements have been used to solve similar issues to improve the efficiency and safety of offshore operations.

Elevated Jackup Site Assessment Validation/Calibration: The industry has a lot of experience conducting field measurements of elevated jackups. Virtually all these programs have been projects specifically aimed to better understanding the behavior of elevated jackups during storms in support of elevated site assessments. In this way, the measurements have addressed either the validation of an analysis methodology or calibration of aspects of models, such as soils (see References 5 and 6). Only a limited number of rigs presently use an on-board measurement system as an operational advisory for rig moves.

Fixed Platforms and Floating Production Units: On-board measurement systems are used extensively on floating production units in the Gulf of Mexico and on fixed platforms worldwide. On Gulf of Mexico FPUs, environmental loadings are measured using wind, wave and current sensors, and sensors for monitoring mooring loads, position (via DGPS), 6 degree of freedom wave frequency motions and riser strain have been installed since the mid-1990s. This information is being used to track fatigue on critical elements (risers and moorings), maximum excursions in storms and during loop / eddy current events and the like. On fixed platforms worldwide, deck accelerometers have been used successfully to support inspection and to detect changes in the natural period that identified brace failure.

ISO Structural Integrity Management (SIM) Standard: One of the centerpieces of the SIM concept in industry standards is the notion that structural measurements are vital in supporting the long-term health of a unit or installation. A program of field measurements designed into an offshore installation at the start of its life is considered a best practice for long-term asset management of a structure.

Operational Advisories for Other Offshore Operations: A variation of the jackup operational advisory systems is used for other offshore operations such as dry transport of jackups or semisubmersibles, hull/deck mating operations, or heavy lift operations. The present state of offshore measurement systems makes them a natural solution for feeding measured data back into operational decision-making, especially when operability due to weather is an issue.

Jackup Operational Advisories: “Prevailing Conditions” and “Operating Limits”

Operational decision-making for jackup moves on and off locations depends on well-founded information on “prevailing conditions” and “operating limits”. If prevailing conditions are within operating limits, the operation can proceed. The quality of the information determines the quality of the decision-making.

Considering the prevailing conditions, the challenge in getting quality information is choosing the correct parameters and making good observations. Typically, general parameters such as seastate and hull motions should be the focus, but more detailed information is also important. Observations (or measurements) of seastate yield important parameters such as significant wave height, peak wave period (or zero-up-crossing period), wave direction, and swell content. Observations (or measurements) of hull motions could include a limited set of parameters such as pitch and roll, or could include comprehensive measurements of all six-degree-of-freedom motions of the hull (i.e., heave, surge, sway, pitch, roll, and yaw) or motions at other locations on the hull or legs.

Considering operating limits, analysis of the jackup model is required under relevant scenarios; i.e., those that are expected during the field operations. The challenge in getting quality results depends on how realistic the analysis is in the following respects:

- Modeling of the jackup, the soils, and the waves at a site

- Simulation of sufficient, relevant operational scenarios for moving on and off location

Operating Limits from the Marine Operating Manual

Operating limits listed in a jackup's Marine Operating Manual (MOM) typically have a simple format and are considered conservative enough to be applicable at most sites. In some industry manuals, a wave height limit of 5 feet is listed with no associated wave period; in other manuals, a wave height limit of 6 feet is listed with an associated wave period of 6 seconds. These are considered suitable for basic sites at which there are few issues with persistent or borderline conditions. These limits are understood to be largely experience-based and don't account for the broader set of parameters such as wave periods, seastate direction, swells, etc.

One difficulty in applying the above MOM limits is that prevailing conditions can have a wave period definition different than that listed in the MOM; and in the case in which no wave period is listed, the information is obviously insufficient. This can leave the site assessor in a quandary.

Another difficulty with the MOM is that when a wave height limit of 6 feet is listed with an associated wave period of 6 seconds, there is room for ambiguity. In some MOMs, wave height means "significant" wave height and in others it means "maximum" wave height by some definition. A similar ambiguity holds true for wave period, where in some MOMs, wave period means "peak" period of the wave spectrum and in others it means the "zero-up-crossing" period.

Considering the above definition issues, operating limits from MOMs should be used with care.

Hull angular motion operating limits are also sometimes included in the MOM. A later discussion on prevailing conditions suggests these limits should also be used with care.

Operating Limits from Comprehensive Analysis

Operating limits can also be determined using jackup assessment methods that go beyond the simple methodology of the MOM. Presently, many jackup designers and consultants use comprehensive assessment methods aimed at determining operating limits – that is, determining what conditions would cause leg stresses or pinion loads to exceed tolerable levels. These methods are useful when developing "nomograms" – sets of results for a range of rig/site parameters – or when developing results for a site-specific location.

Comprehensive assessments at specific locations are beneficial when those locations have persistent or borderline conditions for operability. The generation of these assessments does tend to be costly and require significant calendar time; however, the results go beyond the guidance in the MOM by providing a more detailed picture of the jackup's capability at the location. Figure 1 below shows an example plot of operational seastate limits defined by a curve of significant wave height vs. peak period.

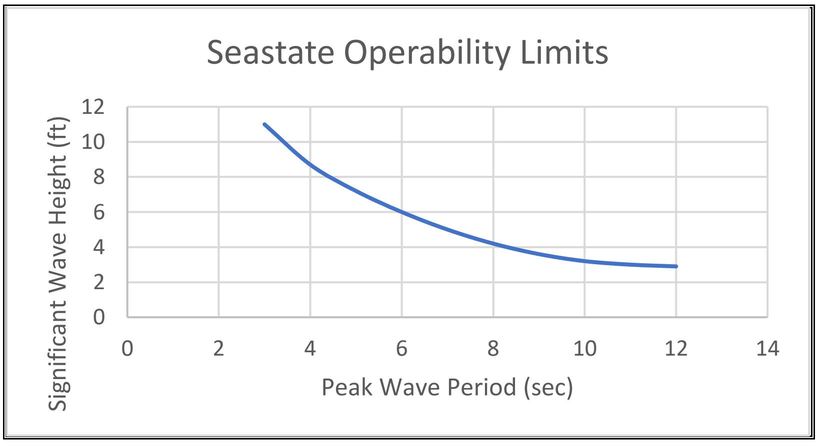

Figure 1 – Seastate Operability Limits

Comprehensive assessment methodologies have improved over the years and currently use models of the jackup that simulate spudcan impact (moving on location) and leg extraction and removal (moving off location). Results are in the form of spudcan velocity (moving on location), wave height / wave period pairs (moving off location), or hull motions (extraction) to map out the operational limits. Typically, the simulations are done for uni-modal, irregular wave spectra and have varying degrees of complexity. Reference 7 presents a method used to assess moving on location that was published two years ago.

Comprehensive assessments can also be used for a range of rig/site parameters to build nomograms in preparation for a jackup's drilling operations. When generating a nomogram for moving on location, spudcan impact is modeled and simulated for different combinations of jackup configurations, water depths, and soil conditions. The simulations are based on scenarios in which the jackup is moving on location and the spudcan is lowered onto the seabed. During this process, the unit's motions cause spudcan motions; and the greater the motions, the greater the impact velocity of the spudcans when they contact the seabed. Ultimately, the loads during impact are driven by the metocean conditions that drive the response of the hull motions and leg/spudcan (six-degree-of-freedom, 6-DOF) and, to some extent, the speed of the pinions lowering the leg influences the process as well.

As noted above, operational limits are defined prior to drilling operations on site based on either the MOM or by comprehensive assessments, or for a specific site or for multiple sites using a nomogram. The approach depends on the criticality of the location.

The assessments described above have advanced in recent years, however as noted below, the methods for gathering information of the prevailing weather conditions either by observation or measurement have not been implemented as well in operational advisories.

Present Jackup Operational Advisories

The operational advisory process for a jackup to move on and off location depends on real-time information on the prevailing conditions. Many jackups still use old-fashioned equipment and processes for observing prevailing conditions that lead to inefficiencies in the real-time operational advisory process.

In the present operational advisory process, the decision to **jack down and move off** location is based on comparing observations of wave height and period to the associated operational limits. For the observations, trained observers (crew members) watch the ocean surface elevation rising and falling relative to a fixed reference point on the jackup – rack teeth or a ladder on the leg. This observation is done for a prescribed interval of time. From this, the observers estimate an agreed-upon wave height parameter – say, significant wave height or some definition of maximum wave height -- and the average time passage between wave crests – generally interpreted as "zero up-crossing period" (T_z) (See Reference 8).

The shortcoming of this seastate observation process is that it does not provide a digital trace of the wave elevation, so it falls short of accurately gathering seastate parameters such as significant (or maximum) wave height, dominant wave period, wave direction, and swell content. Some of these parameters can be estimated from the observations, but since there is no digital data, others cannot.

Regarding wave period, many definitions exist to describe special characteristics of waves and wave spectra. The zero-up-crossing period (T_z) is defined as the time interval between passing wave crests, and can be determined by a trained observer. Without digital data, however, spectral analysis cannot be done to determine a larger set of wave period parameters, especially spectral peak period. The relevance of this will be discussed later in the paper.

In the present operational advisory process, the decision to **move on** location is based on comparing the readings from the level indicators, interpreting them as a true indication of prevailing rig motions, to the associated operational limits. For observation of prevailing rig motions, level indicators are used as an indication of angular motion (pitch and roll). No equipment is available to indicate surge, sway, heave, or yaw.

For moving on location, one shortcoming of this motion observation process is that the level indicator cannot be expected to give accurate dynamic motions readings. Each level indicator uses a bubble in a curved tube of fluid. The primary purpose of this device is to measure the **static** tilt of the hull. When subjected to **dynamic** motions, the device is significantly contaminated by the inertial effects from both lateral accelerations and angular motions. Simply put, it is the wrong tool for this application.

For moving off location after being jacked down into the water, the above shortcoming is apparent in rig observations. Initially, with the spudcans still engaged with the soil it can be agreed that the pitch and roll motions should be insignificant. However, in this situation observations show that the level indicator provides a dynamic "pitch" or "roll" reading (the "bubble" moves). These readings clearly are contaminated by the lateral motions.

Finally, level indicators generally provide no digital data, so processing and storage is not possible.

Modern Jackup Operational Measurements and Advisories

Modern jackup operational measurements and advisories address the shortcomings listed above. Improved real-time information on prevailing conditions can be collected if modern equipment and processes are used. When compared to the old-fashioned observations being made on most jackups today, an approach that employs modern instrumentation provides a step change in identifying weather windows, identifying unexpected hazards, and allowing more clarity for an operator and a contractor to agree on when it's safe to proceed. The sections below provide details for the various stages of the move and benefits are listed in a later section.

Moving on Location – Hull Afloat – Decision to Put Spudcans on Bottom

At the stage when the hull is afloat and moving on location, the operational advisory guides the decision on whether the spudcans can be placed on the seabed. This can only be initiated when prevailing conditions (hull or spudcan motions) are within pre-established operational limits. These limits are set to maintain stresses in the jackup legs and loads in its pinions within tolerable levels when the spudcans contact the seabed.

A standard system for measuring hull or spudcan motions could include either:

- A high accuracy 6 degree of freedom motion inertial package, or
- Three sets of orthogonal tri-axial accelerometers placed at pre-defined locations and orientations on the hull,

During preparations for moving on location, hull motions data are collected and processed onboard the jackup. Data summaries are processed for comparison with the operating limits. Due to the criticality of the operation and the need to avoid delays, automated data quality control processes are used to remove noise from the data. Once noise-free, the motion data can be converted into acceleration, velocity, or displacement data at any point on the jackup.

As the jackup legs are lowered and the jackup prepares to move on location, the prevailing conditions (hull or spudcan motions) continue to be observed by the crew. Automated data transmission allows shore-based personnel to observe if need be. When the prevailing conditions are within operational limits, the decision is then made to move on location.

The data processing used during this operation includes an extreme value analysis technique chosen by the crew or shore-based personnel. The data summary shows results from a limited duration analysis of a very short data record of a few minutes; or a longer data record of several hours. Longer records improve the accuracy, but require more time on the critical path of the operation. The extreme value analysis may utilize the maximum value during the previous time period or a more complex process using the distribution of peaks from the measured data may be employed.

The display of the motion data shows how spudcan motions compare with operating limits in a simple, meaningful display to the rig mover and his team, the on-board management of both the contractor and the operator, and shore-based management of both the contractor and the operator. The display also shows spudcan motion versus time with, for example, one maximum value representing each short data record.

Moving off Location – Hull Elevated - Decision to Jack Down

When moving off location, at the stage with the hull elevated, the operational advisory guides the decision on whether the hull should be jacked down into the water. This would indicate prevailing seastate conditions are within operational limits. Jacking the hull down into the water represents a commitment of time and resources for the leg extraction operations. In addition, with the hull in the water, it will be exposed to wave loading with the spudcans constrained at the seabed, so the legs could see high stresses and the pinions could see high loads. The rig could be exposed to these conditions for a matter of a few hours to a few days.

The prevailing seastate conditions are measured prior to the decision to jack down. The measured seastate is generally in the form of water surface elevation data at the hull gathered by one or more downward-looking airgap sensors. Other data on seastate could be provided by other sensors or sources, but at a higher cost, so for simplicity this discussion will assume the data collected is from airgap sensor(s).

The airgap time histories are processed into wave spectra from which parameters such as significant wave height, peak period, and swell parameters are determined. For this simple approach, wave direction would need to be determined by onboard observations or observations from support vessels or from a metocean forecasting service provider. If both seastate and swell are present, observations can be used to determine the direction of each or they could be provided by the metocean forecast service.

The prevailing seastate conditions are compared to operational seastate limits to determine whether the jackup can tolerate having its hull in the water with its spudcans on the seabed. As noted earlier, operational seastate limits are based on analysis of the jackup to check whether it can maintain a tolerable level of leg stress and pinion loads when exposed to conditions with various significant wave heights and peak periods.

Moving off Location – Hull in Water - Decision to Extract Spudcans

When moving off location, at the stage with the hull in the water, the operational advisory guides the decision on whether the extraction operation should be interrupted by jacking the hull up out of the water. If prevailing conditions (hull motions) or forecasted seastate conditions become excessive when compared to the pre-established operational limits as measured by the advisory system, then the decision can be made based on quantified information. With the hull in the water, it would be exposed to wave loading with the spudcans constrained at the seabed, so leg stresses or pinion loads could be at risk of exceeding tolerable levels.

The prevailing conditions (hull motions) are measured while the hull is in the water. The system of motion sensors provides measurements just as it did during the afloat condition while moving on location. These measurements are converted into hull displacements. Operational limits are preprogrammed into the advisory system based on a structural model of the jackup and are used to determine if the measured displacements are associated with overstressing of the legs or overloading of the pinions.

With the hull in the water and the spudcans constrained at the seabed, the hull should have very little vertical movement at the beginning of the leg extraction process. The hull motion should be primarily horizontal. The advisory system is used to determine if the hull is experiencing too much motion during the extraction process to allow it to continue. If so, the decision is then made to jack the hull back up above the water.

In this configuration, data collection and processing is done similarly to when the jackup was moving on location.

Benefits of a Modern Operational Advisory

- **Rig motion values using electronic motion sensors are accurate.** As noted earlier, bubble type or spirit level indicators widely used at present in the industry are contaminated by rig motions with resulting values that are highly inaccurate in a dynamic environment. A modern set of electronic motion sensors resolves this issue.

- **Seastate observations using a downward-looking airgap sensor are more accurate and comprehensive than using trained observers.** A modern advisory provides spectral results including peak wave period and swell, not just zero up-crossing period. This promotes consistent definitions of wave height and wave period when making comparisons with operational limits.

- **The data process is digital.** This allows the benefits associated with data collection, analysis, storage, and transmission. The drilling contractor and the operator can agree on the equipment and on the pre-established operational limits, leading to a reduction of instances of commercial disputes.

- **Use of the rig for drilling operations service is more attractive to customers and could lead to lower insurance rates.** The service is arguably more predictable and safer resulting in better business decisions at present and future sites. Digital data make it easier to use key performance indicators in a business execution model. Shore-based offices (contractor and operator) can monitor operations in real-time. There are possible insurance benefits.

Example Applications

Drilling Location with Seas and Swell:

For a drilling location with a combination of seas and swell, a modern operational advisory is well suited for the application due to the digital measurement of wave elevation. The presence of swell is generally a critical issue that steps up the importance of the operational advisory. Swell is simply more difficult to observe accurately. The wave elevation measurement is more valuable in this case in that it can be used to detect the magnitude of the swell for application in decision-making. Operational limits would need to be developed using site-specific assessment methods related to both seas and swell. These could then be used as limits for the anticipated prevailing seas and swell and for the prevailing rig motions responding to these.

Reference 8 describes seas and swell as follows:

"The wave conditions in a sea state can be divided into two classes: wind seas and swell. Wind seas are generated by local wind, while swell have no relationship to the local wind. Swells are waves that have travelled out of the areas where they were generated. Moderate and low sea states in open sea areas are often composed of both wind seas and swell."

Spectra that can be used to represent wind seas only are the Pierson-Moskowitz (**PM**) spectrum or, a more general representation of it, the Jonswap spectrum. Wind generated waves are irregular, and when they are represented as a PM or Jonswap spectrum, the highest point in the spectrum is represented as peak period (**T_p**). As noted earlier, T_p cannot be measured by, for example, observing waveforms in the ocean. Digital wave-elevation data must be transformed into a spectrum to make this observation.

Figure 2 below shows a plot with uni-modal Jonswap spectra of various γ peak enhancement factors.

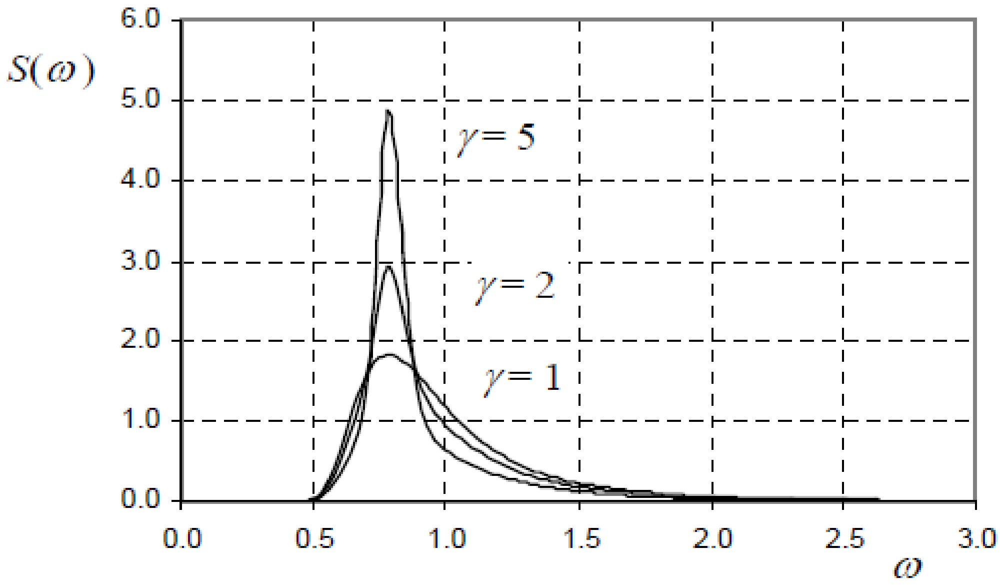

Figure 2 – Jonswap Spectra

When seas and swells are both present in a wave spectrum, operational limits are undoubtedly more complex to generate and apply in the operational advisory. The prevailing conditions can be represented as a "bi-modal spectrum" – that is a spectrum with two peaks. A commonly defined bi-modal spectrum is the Ochi-Hubble spectrum discussed in References 9 and 10. This spectrum can be defined with six parameters – significant wave height, spectral peak period and a spectral shape factor, i.e., (H_s, T_{pj}, λ_s) for each peak. Reference 10 describes a typical method for modelling sea states that include both sea and swell components. Having modern instrumentation with a digital measurement of wave elevation enables or improves the operational advisory for this more complex scenario. Figure 3 below shows a plot of a typical Ochi-Hubble spectrum illustrating two peaks.

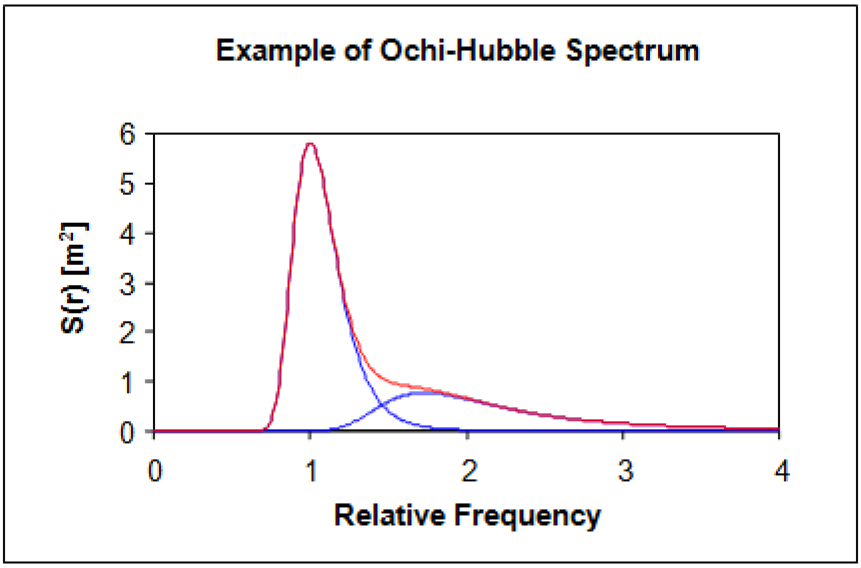

Figure 3 – Ochi-Hubble Spectrum

Extraction Difficulties

For locations with leg extraction difficulties, the operational advisory is critical to the decision of whether the hull motions are excessive and the hull needs to be jacked back up out of the water. In cases with legs that are taking a long time to extract, the length of time in the water makes the measurement of hull motions more critical than normal. Fatigue or wear could become an issue, so information on the prevailing lateral motions is important.

Another issue is the changing leg fixity boundary conditions as spudcans release from the seabed. Data from the motion sensors can be used to help assess changes in the natural period and any sign of vertical movement. Operational limits may have been developed based on a single fixity boundary condition, or they may have accounted for various scenarios such as one leg free, two legs free, three legs free, or one or more legs out of the spudcan hole. The motion sensors provide information to assist in understanding the prevailing response. Overall, information gathered from the instrumentation helps to understand the condition of the jackup during the removal as it transitions from a fixed structure to a floating structure.

Reference 11 shows relevant analysis work done for a jackup undergoing leg extraction, showing the effects of changing spudcan fixity.

Unique soils

The modeling of soils in spudcan impact analysis is important in the operational advisory process for moving on location. As noted earlier, the operational limits need to be pre-established for the site, either using site-specific analysis or using nomograms. The use of nomograms may be appropriate to determine operating limits for moving on location for a range of sites; however, at times site-specific analysis may still be the only way to get accurate information for sites with unique soils.

Nomograms are typically generated through simulations of moving on and off location, and they are done in advance to produce limiting wave height versus wave period plots for a range of rigs, water depths, and soil conditions. The soil models used in nomograms have limitations due to uncertainties in the soil properties.

In addition to the benefits of the hull motions measurements to the operational advisory process, further value might be found in a validation/calibration process. As a longer-term objective, with improved measurements of seastates from the afloat hull, prevailing hull motions may be compared against predicted hull motions to improve the analytical model. This is a step outside of the operational advisory process.

Further Benefit for Elevated Case

Without making any modifications, a modern instrumentation system such as that described here for the process of moving on and off location has substantial benefits for gathering data in the elevated condition as well. Soils are generally the greatest uncertainty for elevated site assessments and events such as severe storms, scour, and penetration during preloading can make actual leg foundation fixity different than expected. By simply keeping the instrumentation working, leg foundation fixity can be checked using the hull motions data processed to get natural period. Using a structural model calibration step, this can then be converted into leg foundation fixity. This information has value; at the current site and at future sites in the field.

Conclusions

This paper shows the benefits of modern instrumentation when applied to an operational advisory process for jackup moves on and off location. A case is made that this is an industry need and that, although it requires a change in the current industry practice, the technology is there and able to be implemented. The decision-making process during jackup moves was discussed to identify the specific improvements resulting from modern instrumentation. A list of benefits was developed and applications with marginal or persistent conditions were identified that could be enabled, improved, or have extended benefits from modern instrumentation. When deployed, such instrumentation will lead to less time spent waiting on weather, reduced exposure to risk of incidents, and fewer commercial disputes between operators and contractors.

References

1. American Bureau of Shipping, "Guidance Notes on Self-Elevating Unit Motions Monitoring", Confidential (available via NDA), July 2016.
2. J. Brekke, J. Murff, R. Campbell and W. Lamb, "Calibration of Jackup Leg Foundation Model Using Full-Scale Structural Measurements," *Offshore Technology Conf.,* Houston, TX, 1989
3. J. Brekke, R. Campbell, W. Lamb and J. Murff, "Calibration of a Jackup Structural Analysis Procedure Using Field Measurements from a North Sea Jackup", *Offshore Technology Conf.,* Houston, TX, 1990
4. D. Stock, J. Brekke and C. Liaw, "Jack-up Response Measurements from Hurricanes Katrina and Rita", 12th International Conference on the Jackup Platform, City University, London, 2009.
5. J. Templeton, D. Lewis and J. Brekke, "Spud Can Fixity in Clay, First Findings of a 2003 IADC Study", *Jack-up Conf.,* City University, London, 2003.
6. J. Templeton, D. Lewis and J. Brekke, "Assessment of Jack-up Survival in Severe Storms", *Offshore Technology Conf.,* Houston, TX, 2009.
7. P. Tan (ABS), X. Chen (ABS), Q. Yu (ABS), M. Perry (Keppel), H. Mu (Keppel), T. Chang (Bennett), M. Wong (Bennett), D. Chen (Genesis), "Jackup Going on Location Analysis", 15th International Conference on the Jackup Platform, City University, London, 2015.
8. DNV Recommended Practice DNV-RP-H103 'Modelling and Analysis of Marine Operations' (April 2011, revised December 2012).
9. DNV, Environmental Conditions, 34 [3.5.7.4]; Knut Torsethaugen, 'Simplified double peak spectral model for ocean waves', SINTEF Paper No 2004-JSC-193.

10. See Orcina, OrcaFlex Environment: Data for Ochi-Hubble Spectrum, https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/Help/Content/html/Environment,DataforOchi-HubbleSpectrum.htm, April 4, 2017.
11. Partha Chakrabarti, Sanjay P Joshi and Manjoy K Maiti, 'Pull-down analysis of Jack-up rigs' (2007) in *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering*.