Modern Jack-Ups and their Dynamic Behaviour

Investigating the trends and limits of moving into deeper waters

T. Koole
MSc Thesis at the department of Offshore Engineering
Delft University of Technology, The Netherlands

M. van der Kraan
Civil, Structural & Offshore Engineering
Shell Global Solutions International

Abstract

This paper describes an analysis of modern jack-up designs. Trends throughout the various designs are identified and justified. The environmental loads and dynamic response of these modern designs are analysed using the methodology as described in current guidelines. Furthermore, the water depth limit of current design philosophy is investigated. This research shows that as water depths increase, jack-ups become more wind-dominated in terms of environmental loading. A more detailed wind load calculation method, than the currently used projected-area method, is therefore recommended. Furthermore the need for increasing chord spacing is identified in an attempt to retain a stiffness dominated structure. This however increases the risk of problems associated with Rack Phase Difference (RPD) which occur during jacking operations and therefore illustrates a conflict within the design of jack-ups as the industry heads for deeper and deeper waters.

***Keywords**: Jack-Up, deepwater, dynamics, dynamic response, limits, RPD.*

Introduction

Jack-ups have been used since the mid 50's and have grown to become the most widely used Mobile Offshore Drilling Unit (MODU). The Site Specific Assessment (SSA) procedure for these structures was harmonized in the late 80's in a JIP which involved various rig designers, owners and operators. Although the topic of jack-ups in elevated condition has therefore enjoyed a significant amount of interest in the end of the 19th century, efforts to keep up with the ever changing market have remained limited over the last years. The thesis described in this paper was an attempt to bridge this gap.

Modern jack-ups and failure rates

Pre-millennium jack-ups were identified to have relatively high failure rates when compared to fixed structures [1]. Although rig designs have evolved, the failure rates of modern jack-ups still remain relatively high. During the 1996-2009 interval, 296 jack-up related incidents were reported. These involved the deaths of 60 people [2], [3] and [4]. This indicates the need for further study regarding the topic of jack-ups. Currently, a large share of these failures occur during jacking operations. Braces are damaged when a rig experiences a punch-through, or when excessive RPD is seen within a leg. This latter failure-mode is typically one which is seen to occur more often with modern rig designs and has therefore enjoyed a significant amount of attention throughout recent years [5], [6] and [7]. The UK HSE watchdog published a report on the matter in 2004.

Market Analysis

A market analysis was used as a starting point for the thesis described. The major design parameters of 41 jack-ups were gathered and compared. These represent the majority of designs that have been introduced over the last 30 years by different jack-up designers. The results are given in Figure 6 and Tables 4 and 5. Across the modern jack-up designs (age < 20 years) the following trends were identified:

- **Fixations system:** All modern design use rack chocks to form the leg-hull connection. Bending moments are no longer transferred through horizontal shearing forces imposed on the legs by the guides, but are transferred through a vertically directed couple instead. This reduces the required bracing strength, thus reducing the weight of and hydrodynamic loads on the legs as jack-ups move to deeper waters.

- **Leg Design:** X-bracing and large chord spacing is used by all designers to achieve leg designs with high moment of inertia. The resulting system there remains stiffness dominated which is required to prevent excessive dynamic response at greater water depths. However, the long slender braces become prone to buckling due to RPD during jacking operations. Figure 7 shows the evolution of leg designs used by F&G as their rigs are designed for deeper water and harsh conditions.

Environmental Loads

In-situ jack-ups are mainly exposed to environmental and gravitational loads. The environmental loads act predominantly in the horizontal direction and can be expressed in terms of a Base Shear (total lateral forces) and an Overturning Moment. Gravitational forces act in the vertical direction and are caused by permanent and variable loads. The forces are transferred into the seabed through the soil-structure interface which is formed by the spudcans. Figure 1 shows the general loads on a Jack-Up in elevated condition.

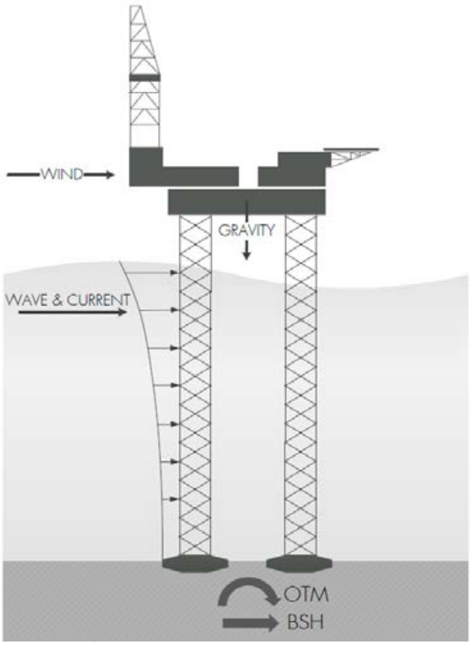

Figure 1: Environmental, gravitational and (resulting) foundation loads for typical jack-up in elevated condition.

Wind Loads
Wind loads are directly proportional to wind areas. These are dominated by hull area. As jack-ups get bigger, wind areas increase accordingly. Figure 2 shows wind areas for different jack-up designs:

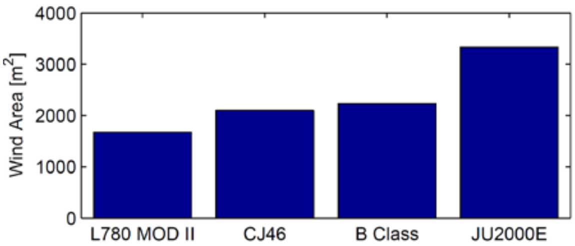

Figure 2: Wind areas of different rig designs, with increasing water depth capabilities from left to right.

Hydrodynamic Loads
The move towards deeper waters requires increased leg stiffness to prevent both excessive sway due to environmental loads and resonance due to wave loads. This is achieved by increasing chord spacing which leads to longer braces and therefore increased hydrodynamic loads. The hydrodynamic parameters of five common rig designs are given in the table below (Table):

Table 1: Hydrodynamic Parameters for different rig designs

Rig Design	D_e*C_D	C_{A_e}*A_e
F&G MOD II	3.64	2.58
F&G MOD V	4.01	3.92
KFELS B Class	4.52	3.58
F&G JU2000E	4.59	3.46
Gusto CJ62	5.35	5.46

As jack-ups are drag-dominated structures in terms of hydrodynamic loading the increase in D_e*C_D is governing. For larger rigs, this increase is counteracted by a reduction in wave load due to the increase in leg spacing. Increased leg spacing results in a larger phase difference between the loading on the three legs.

For this reason, wind loads become more dominant in modern jack-ups. This is an important observation as wind loads are often calculated using the projected-area method. Several studies have shown however, that the projected-area method gives conservative results [8], [9]. This places an unnecessarily high burden on the assessment of the structure and also raises the required pre-load.

Dynamic Response

Jack-ups often see natural periods approaching the periods of high energy waves (10-15s). Therefore, relatively high Dynamic Amplification Factors (DAFs) are found for jack-ups in elevated condition. Due to non-linearities within the structure (p-delta) and loading (drag-term and stretching effects) time-domain FEM analysis is often the preferred method to quantify dynamic response of a structure. A simplified model was used in order to minimize simulation time:

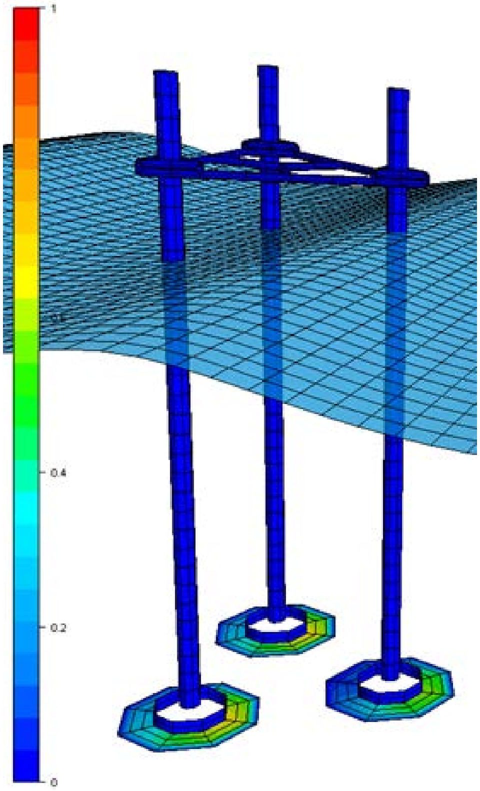

Figure 3: Simplified FEM model used for dynamic response analysis.

Two models were created in order to understand the general behaviour of modern jack-ups. Model A represents the small modern jack-up designs currently popular in the market (GustoMSC CJ-50, KFELS B-Class, F&G JU2000E). Model B represents the big modern jack-up designs (GustoMSC CJ-70, KFELS N-Class). The dynamic properties of both models are given in Table 2.

Table 2: Dynamic analysis input parameters, model A and B

Property	Model A	Model B
Leg Spacing [m]	50	65
Bay Height [m]	10	10
Nr. of Bays [-]	16	19
Hull Weight [t]	14000	18000
Leg Weight [t/m]	10	11
Leg buoyancy [t/m]	1.5	1.7
Chord Spacing [m]	12	16
Spudcan Diameter [m]	18	22

Natural Periods

The natural periods of the first vibration mode in sway/surge direction for the two models in various water depths were calculated using modal analysis. These are most likely to be excited since they are often similar to the periods of high energy waves. Furthermore, the profile of the wave loads along the vertical legs is likely to excite the first vibration modes of the structure. The natural periods of model B for various modelling conditions is given below:

Table 3: Natural periods for model B in various water depths and spudcan models

	Spudcan Model		
WD [m]	**Fixed**	**80%**	**Pinned**
90	3.3	4.2	6.6
100	3.7	4.7	7.6
110	4.1	5.3	8.6
120	4.6	6.1	10
130	5	6.7	11.2
140	5.6	7.5	12.6
150	6.1	8.4	14.2

The natural periods approach the periods of high energy waves when water depth increases and fixity decreases. The difference between fixed and pinned spudcans indicates the importance of obtaining accurate soil data prior to evaluating the expected dynamic response.

Regular Waves
DAF spectra were produced for both models in various water depths and spudcan conditions. These were used to validate the behaviour of the model and also give insight into the nature of the dynamic response. Fig. 4 shows the DAF spectrum for the A100P model, which implies 100m of water depth and pinned foundation:

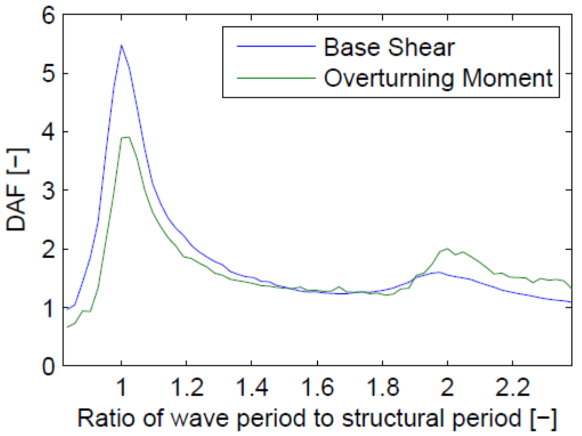

Figure 4: DAF spectrum for regular wave test model A100P.

The figure clearly shows the resonance peak at T_p/T_n=1 as would be expected for the system under consideration. Furthermore, an additional (smaller) response peak is seen at T_p/T_n=2. This indicates the presence of a higher order terms within the wave loading. For drag-dominated structures like jack-ups, these originate from the following sources:

- **Drag-term:** The drag loading term in Morison's equation contains a $v|v|$ term which has a Fourier harmonic component at odd fractions of the wave period ($T_w/3, T_w/5$…).
- **Stretching:** Stretching the wave kinematics to the actual sea-surface instead of the Mean Sea Level also induces higher order harmonics on the wave loading. These show at both even and odd fractions of the wave period ($T_w/2, T_w/3$…)

Because the drag-term only leads to odd high order terms, the additional resonance peak seen in Fig. 4 is attributed to stretching effects. These effects cannot be captured in a linear analysis which stresses the need for non-linear techniques.

Irregular Waves
Irregular wave runs were performed to calculate DAFs for various water depths and spudcan modelling conditions. The DAFs were calculated using 3-hour storms, where the model was run quasi-statically (no inertia) and dynamically. The 1st, 2nd, 3rd and 4th moments of the BSH and OTM time traces were then used to calculate the DAFs for both parameters. This procedure uses the Winterstein-Jensen method as described in the guidelines. The results are plotted in Fig. 5:

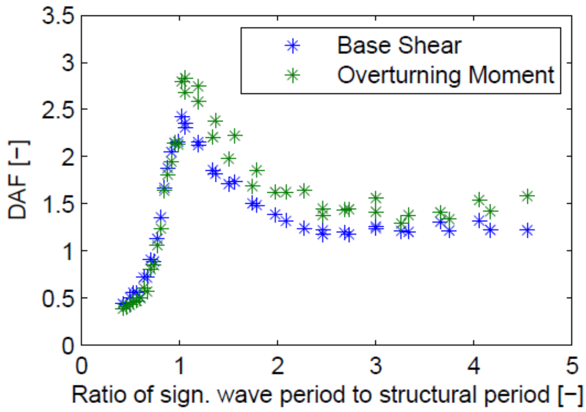

Figure 5: Results for irregular wave runs. Clearly showing typical dynamic response spectrum with resonance peak at T_p/T_n.

Worst-case dynamics lead to DAF's of up to 2.5 for BSH and 3 for OTM. The height of this resonance peak is determined mostly by the damping in the system (2% structural, 2% soil and relative velocity for hydrodynamic damping). These results show why jack-ups are designed to remain stiffness dominated ($T_n<T_p$); when the natural period of the structure is half the significant wave period, DAFs drop below 2 and therefore decrease the magnitude of the inertial load set applied in the assessment.

Limits

The current design philosophy is aimed at achieving a stiffness-dominated system. This prevents resonance due to wave loading. As jack-ups are designed for increasing water depths their mass increases. A study at Louisiana State University concluded the mass increase of the structure is found to be exponentially proportional to water depth increase [10]. This finding was used to derive a relationship between water depth increase and required leg moment of inertia increase:

$$I \propto WD^5 \quad (1)$$

The moment of inertia of a jack-up leg is a function of chord spacing h and chord area A_c to give:

$$WD^5 \propto h^2 A_c \quad (2)$$

These relationships show the reasoning behind rapidly growing chord spacing in recent jack-up designs. Relatively small increases in water depth require a large increase in leg stiffness to maintain a stiffness-dominated system. The relationship given by Eq. (2) is however bound to the following limits:

- **Chord Spacing:** Large chord spacing is associated with increased risk of brace buckling during jacking operations as a result of RPD.
- **Chord Area:** Currently, chord are fabricated by rolling two u-shaped sections and welding these to a rectangular-shaped steel centre-piece which holds the racks. The thickness of the u-shaped sections is relatively large compared to the diameter of the rolled section.

Conclusion

Modern jack-ups are characterised by large triangular hulls, housing three spacious truss legs. Rack-chocks allow use of slender bracing as chord space increases to achieve high leg stiffness. This however also leads to increased occurrence of problems during jacking operations.

Modern jack-ups are more wind-dominated in terms of environmental loads when compared to their predecessors. Hull areas and therefore wind loads increase rapidly, but the slender braces and increased leg spacing prevent the hydrodynamic loads from increasing at the same rate. The conservative projected-area is therefore not suitable for the SSA of modern rigs as it places an unnecessary burden on the assessment.

Most of the modern jack-ups are being designed for deeper water depth (175m or more). The leg stiffness required at greater water depths becomes challenging to achieve; high chord spacing leads to more problems during jacking operations and increased chord areas become more difficult and expensive to fabricate.

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	70's	80's		90's		2000's		2010's
LeTourneau	116-C	200-C			219-C	225 Tarzan	116-E 240C EXL	Gorilla XL
F&G		L-780 L-780 MOD II	L-780 MOD V L-780 MOD VI	M2		JU2000E JU2000A	Super M2	
KFELS					A-Class	B-Class Super B-Class	Super N-Class	Super A-Class
GustoMSC		CJ46	CJ50	CJ62		CJ70		CJ80
BMC						Pacific 375		Pacific 400

Figure 6: Major jack-up designs introduced over the last 40 years

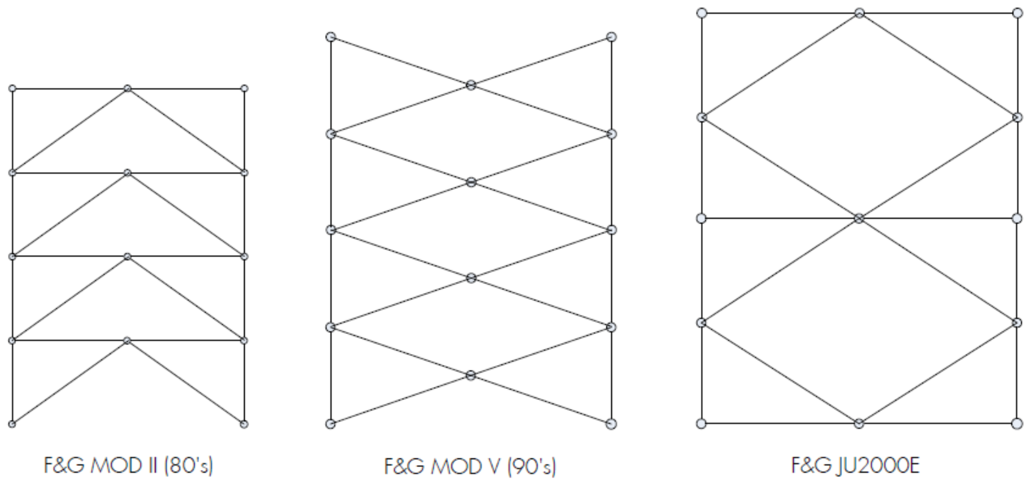

Figure 7: Leg designs used by F&G, decreasing in age from left to right.

Table 4: Main characteristics of all Jack-Up designs - Part 1

		Depth		*Leg*	*Hull dimensions [m]*				*Leg Spacing*		*Chord*	*Footing*
Make	*Type*	*[FT]*	*[m]*	*Length [m]*	*L*	*B*	*D*	*Leg Shape*	*Long.*	*Transv.*	*Distance [m]*	*Area [m^2]*
GustoMSC	CJ46-X100-D	375	114	154	65.3	62.0	8.0	▲■	46.0	40.0	10	150
GustoMSC	CJ50-X100-MC	350	107	-	70.0	68.0	9.5	▲	50.0	43.3	12	-
GustoMSC	CJ50-X120-E	400	122	163	70.0	68.0	9.5	▲	50.0	43.3	12	200
GustoMSC	CJ62-120S	400	122	175	78.2	90.3	10.8	▲	62.0	53.7	16	250
GustoMSC	CJ62-X130-A	425	130	185	80.9	87.6	11.0	▲	62.0	53.7	16	314
GustoMSC	CJ70-X150-B	492	150	207	88.8	102.5	12.0	▲	70.0	60.7	18	380
GustoMSC	CJ70-X150-MC	492	150	203	88.8	102.5	12.0	▲	70.0	60.7	18	380
GustoMSC	CJ70-X150-MD	492	150	-	88.8	105.1	12.0	▲	70.0	60.7	18	-
GustoMSC	CJ80-X175-A	574	175	232	101.0	110.0	13.0	▲	80.0	69.3	20	420
F&G	L-780	350	107	131	54.9	53.3	7.6	▲	36.6	35.1	-	111
F&G	L-780 MOD II	300	92	-	54.9	52.7	7.6	▲	36.6	35.1	-	111
F&G	L-780 MOD V	350	107	-	69.5	67.7	9.4	▲	-	-	-	-
F&G	L-780 MOD VI	394	120	-	74.4	76.2	11.0	▲	-	-	-	-
F&G	Super M2	300	92	125	62.8	55.8	7.6	▲	36.6	35.1	9.9	115
F&G	JU2000A	350	107	150	75.5	72.0	8.2	▲	39.6	21.6	11.9	229
F&G	JU2000E	400	122	167	70.4	76.0	9.4	▲	47.6	45.7	13.1	254
F&G	JU3000	400	122	171	70.4	84.5	9.4	▲	47.5	45.7	13.1	-
F&G	UniversalM	400	122	171	79.1	91.7	10.7	▲	54.3	46.6	16.8	378
KFELS	MOD V A Class	400	122	-	75.0	67.7	9.4	▲	47.5	45.7	-	254
KFELS	MOD V B Class	400	122	-	68.6	63.4	7.6	▲	43.3	39.3	11.9	161
KFELS	A Class	400	122	166	75.0	67.7	9.4	▲	-	-	-	-
KFELS	B Class	400	122	158	71.3	63.4	7.6	▲	43.3	39.3	-	154
KFELS	Super B Class	425	130	148	75.0	66.4	7.6	▲	43.3	39.3	-	197
KFELS	Super A-Class	400	122	160	75.0	73.2	9.4	▲	47.5	45.7	-	254
KFELS	N-Class	425	131	173	80.5	88.0	10.7	▲	62.8	53.9	-	-
KFELS	MOD VI Universe Class	394	120	-	74.4	76.2	11.0	▲	-	-	-	254

Table 5: Main characteristics of all Jack-Up designs - Part 2

		Depth		*Leg*	*Hull dimensions [m]*				*Leg Spacing*		*Chord*	*Footing*
Make	*Type*	*[FT]*	*[m]*	*Length [m]*	*L*	*B*	*D*	*Leg Shape*	*Long.*	*Transv.*	*Distance [m]*	*Area [m^2]*
LeTourneau	64	350	107	-	72.2	61.0	7.9	■	-	-	-	154
LeTourneau	84-CE	350	107	-	72.5	69.2	7.9	■	43.3	39.3	-	154
LeTourneau	116-C	300	92	125	74.1	61.0	7.9	■	43.3	39.3	-	154
LeTourneau	Super 116-C	350	107	145	74.1	62.8	7.9	■	43.3	39.3	-	154
LeTourneau	Super 116-E	350	107	145	75.0	63.0	7.9	■	43.3	39.3	-	154
Rowan	200C Gorilla	450	137	194	90.5	89.0	9.1	■	64.0	57.6	-	-
Rowan	219C Super Gorilla	400	122	185	93.3	91.4	11.0	▲	66.4	57.6	-	-
Rowan	224C Super Gor. XL	490	149	197	93.3	91.4	11.0	▲	66.4	57.6	-	-
Rowan	225C Tarzan	300	92	136	65.5	59.7	6.7	▲	43.0	37.2	-	-
Rowan	240C	350	122	150	69.5	67.1	7.9	■	43.3	39.3	-	-
Rowan	EXL	350	107	145	74.1	62.8	7.9	■	43.3	39.3	-	-
Baker Marine Pacific	Class 250	350	107	146	71.9	71.9	9.1	▲	-	-	-	-
Baker Marine Pacific	Class 375	375	114	154	72.1	68.4	8.5	▲	47.2	44.2	13.25	221
Baker Marine Pacific	Class 400	400	122	162	72.2	68.4		-	-	-	-	-
Hitachi Zosen	K-1032N	250	76	158	70.1	76.2	7.0	-	57.3	50.0	-	148