## Modern Jack-Ups and their Dynamic Behaviour

Investigating the trends and limits of moving into deeper waters

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Investigating the trends and limits of moving into deeper waters

MASTER OF SCIENCE THESIS

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## Abstract

Jack-Ups have been used since 1954, and have become the most widely used Mobile Offshore Drilling Unit (MODU) for offshore exploration and development purposes that are carried out by oil companies such as Shell. They have been a subject of much research during the end of the 1980's, but have seen limited publications since the change of the millennium. In the meantime, the industry has seen the introduction of a new breed of Jack-Up designs, capable of operating in water depths up to 170 meters in harsh environments such as The North Sea. In order to ensure safe operation of these newer Jack-Ups, a study is carried out to update Shell's in-house knowledge. This allows the company to gain more insight into the various designs available and also helps to identify the governing design parameters within Jack-Up assessments. Furthermore, the future of Jack-Up designs is investigated as it will help Shell shape prospective offshore developments.

A market analysis identifies the trends within Jack-Up designs which can be used to generate the models used in the main body of this research. Quasi-static environmental loads are analysed to investigate the effects of using Jack-Ups in greater water depths. The dynamic response is then added as Jack-Ups are known to show significant dynamic behaviour. Timedomain FEM is used as it allows for the incorporation of the non-linearities that are present in the system. The final chapters of this thesis focus on the future of Jack-Up design. Firstly, the limits of the current design philosophy are identified. Secondly, four possible solutions to overcome these boundaries are proposed and briefly analysed to evaluate their potential.

This thesis has shown that modern Jack-Ups are characterised by large triangular hulls, holding three spacious truss legs. Rack-chocks form a very stiff leg-hull connection which has allowed designers to reduce brace diameters and increase chord spacing. This has lead to an increase in problems associated with Rack Phase Difference. Wind loads increase significantly with these modern rig designs but wave loads remain fairly unchanged due to increased leg spacing. Modern Jack-Ups therefore become more wind-dominated when compared to older designs. This stresses the need for accurate calculation of wind-loads during Jack-Up assessment. The dynamic response analysis and its non-linearities remain to play an important role in the assessment of the structure. Significant dynamic amplification of the oscillating wave loads is found. The future of the current Jack-Up design philosophy is limited to approximately 200 meters. As hull weights and water depths increase, a strong increase in leg stiffness is required to prevent resonance from occurring. Fabrication and operational limits prevent the stiffness from increasing further. Solutions to overcome these boundaries show the difficulties of designing hybrid structures like Jack-Ups; improvements made in one area will often lead to compromises being made in another.

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# 1

## Introduction

The ever growing global demand for oil and gas requires more and more wells to be drilled offshore. The majority of these wells are drilled by a fleet of Mobile Offshore Drilling Units (MODUs), consisting of Jack-Ups, Semi-Subs, Drillships and Drill Barges. Within the MODU fleet Jack-Ups are the most common type of drilling rig, making up almost 60% of the total fleet.<sup>1</sup> Jack-Ups are hybrid structures with a hull that allows them to float, and legs that allow them to stand on the seabed. They are towed to location where jacking mechanisms drive the legs into the soil and raise the hull above the water surface.

Traditionally, Jack-Ups were only used in relatively shallow water depths of less than threehundred feet and mild environments, but as the easy oil fields are being depleted the Jack-Up fleet is pushed towards deeper waters and harsher environments. Currently, these environments are dominated by semi-subs. However, the cost benefit of employing Jack-Ups has lead to the introduction of ultra-premium Jack-Ups. These are capable of handling water depths up to five-hundred feet in harsh environmental conditions. Jack-Ups are popular because they have relatively low building costs and day-rates, while their bottom founded nature also gives a number of advantages over floating drilling solutions:

- Possible placement over jackets
- Relatively simple well design
- Allow use of surface BOP
- Less downtime

<sup>&</sup>lt;sup>1</sup>www.rigzone.com

## 1-1 Problem Definition

The companies that are involved with MODU drilling Jack-Ups can be grouped according to their function. Rig designers sell designs or built rigs to drilling contractors. These own the rig and offer their Jack-Ups for rent or lease to oil operating companies who invest in the wells that are drilled. The classification societies overlook the market to ensure that rigs meet the rules and regulations that apply. Classification societies often also double as warranty surveyors to cover the insurance of Jack-Up operations in a field location. This structure is shown in the figure below (Figure 1-1):



**Figure 1-1:** Companies that comprise the MODU Jack-Up market: Rig designers sell designs to the drilling companies which are in turn contracted by oil companies to drill the wells. Classification societies maintain technical standards.

Although Jack-Ups are often owned and operated by drilling companies, the oil companies that use them in the development of their oil fields are partially responsible for safe operations. For this reason the CSO department within Shell offers engineering support to operating units. The engineering is partially outsourced however, and the change of the millennium has seen the introduction of a new breed of Jack-Up designs capable of operating in water depths easily exceeding 120 meters. The industry nor Shell has seen research into these newer designs capable of operating in deeper waters.

For these reasons, the in-house knowledge on the topic of Jack-Ups has become outdated. There is a lack of insight into the various Jack-Up designs available. Furthermore, by outsourcing part of the engineering no 'feel' is created into the various parameters that influence the assessment of Jack-Ups. The limits in terms of water depths also remain unknown.

A study that refreshes Shell's in-house knowledge is therefore suggested.

## 1-2 Research Objectives

Preceding the main research objectives is an investigation into the assessment of Jack-Up designs and available literature related to this topic. The thesis will then be structured to achieve the following objectives:

- 1. Identify the trends within Jack-Up designs using market analysis
- 2. Quantify the consequences in quasi-static global loads when moving to deeper water and harsh environments
- 3. Evaluate the dynamic response to be expected by modern designs in deep water conditions
- 4. Identify critical limits that bound current design methodology
- 5. Investigate possible solutions to overcome the limits identified in objective 4

#### Scope

This thesis is limited to an analysis of the structural aspects of modern, *in-situ* Jack-Up designs to emphasize the mechanical engineering background of the candidate. This thesis therefore excludes a detailed analysis of the soil mechanics that occurs in the soil foundation supporting the structure. This thesis also excludes the afloat situation as it is a maritime engineering topic.

### **1-3** Thesis Structure

Chapter 2 gives a summary of the literature associated with the assessment of elevated Jack-Ups. This includes both industry guidelines and external studies on the topic. This chapter also briefly covers the trends within failures for *in-situ* Jack-Ups.

Chapter 3 continues by describing the results of a market analysis which was performed to identify the 'modern' designs capable of operating in deep water and harsh environments. The analysis also reveals changes in design philosophy of rigs introduced over the last 20 years. A brief overview of the history of Jack-Up design is also included for completeness.

Chapter 4 covers quantifying the loads on the Jack-Ups that were identified in the previous chapter. In this chapter, the dynamic response of the structure is neglected and environmental loads are estimated and applied to a simplified Jack-Up model to determine estimates for base shear and overturning moment. These results can be further used to determine estimates for the reaction forces at the spudcans. The analysis approach uses a combination of existing guidelines and Ultimate Strength for Offshore Structures (USFOS), a computer program that performs analyses of space frame structures like jackets and Jack-Ups.

Chapter 5 introduces the available methods of incorporating dynamic response into the analysis. The choice of time-domain finite element method is justified and then explained. FEM modelling and general parameters of Jack-Ups are discussed. The IT structure used to efficiently perform batch runs is also explained.

Chapter 6 presents the results of the dynamic response analysis. The model is validated by identification of the vibrational modes. Added to this is the generation of a Dynamic Amplification Factor spectrum using regular wave test which also allows validation of the numerical model. The chapter then presents the obtained DAFs resulting from irregular sea-states. Different sub studies are performed and discussed.

Chapters 7 and 8 is a study into the future of Jack-Up designs. Limits of current design philosophy are identified and possible solutions are proposed and analysed.

Chapter 9 is the final chapter of this thesis which presents the conclusions and recommendations made after completion of the research described in the preceding chapters.

2

## **Assessment & Associated Literature**

Due to their mobile nature, Jack-Ups are used in a large number of different locations throughout their lifetime. For this reason, Jack-Ups are assessed before each rig-move to ensure the structure is capable of withstanding the combination of water depth, met-ocean- and soilconditions that characterize a specific location. In the 80's, with the rapidly increasing computational power available to the companies involved in the Jack-Up market, possibilities for performing detailed assessments were growing. Rig designers and operators developed their own assessment methods. This lead to differences in results. Towards the end of the 1980's Shell also started to assess Jack-Ups using internally developed guidelines. This allowed a critical look into the assessment process, the various assumptions involved and the uncertainties they lead to in the final result. It was noticed that there was little consistency in the results different assessors produced using their internally developed guidelines. Shell therefore initiated a study in which 16 companies completed a survey and 14 of them performed a case study on fictional Jack-Up designs.

## 2-1 SNAME Guidelines

The study confirmed Shell's finding on the large spread of results throughout the various companies in the industry. In 1989 a Joint Industry Project (JIP) was initiated in an attempt to harmonize assessment guidelines in order to improve the consistency of assessment results. The JIP involved representatives from rig designers, drilling contractors, oil companies and classification societies. The result was the "Guidelines for Site Specific Assessment (SSA) of Mobile Jack-Up Units", published by the Society of Naval Architects and Marine Engineers (SNAME) in 1991. This document covers the full assessment procedure which is to be completed when a Jack-Up is used at a given location. It allows the user to perform Jack-Up assessments independently whilst assuring consistent results throughout the industry. It has been reviewed an updated by the SNAME and has been converted into an ISO form (ISO 19905-1/2) which was published in 2012. These documents are the result of a large number of studies completed by the industry and hence make up the backbone of the literature used in this thesis.

The development of the SNAME guidelines was accompanied by a variety of studies before and after its publishing. These can be divided into several areas of which details are given in the sections below.

**Hydrodynamic Loading** was extensively researched during the development of the SNAME Guidelines. Wind tunnel test results and a study by Delft Hydraulics reviewed by DNV resulted into a method for calculating the hydrodynamic properties of truss legs as used in Jack-Ups. An evaluation of hydrodynamic load calculation for truss structures in jackets was performed by [Gudmestad and Moe, 1996] who concluded low drag term assumptions (Cd = 0.7) may lead to non-conservative results. More recently, a Jack-Up specific study was performed by [Lee et al.] in which wave loads on a single leg bay were calculated using two different methods. The first was done using the SNAME guidelines method which involves Morison's equation whilst the second method involved performing CFD simulation on a leg bay. The research showed resulting base shear and overturning moment values differed by 25% when comparing the two methods.

Wind Loading has become more important as Jack-Ups are employed in harsh environments which involve higher wind speeds. SNAME Guidelines stipulates use of the projected area. Even before publishing of the guidelines, research showed the projected area gives conservative results [van Walree and Willemsen, 1988]. Twenty-five years later, [Hu et al.] performed a research study where wind test of a Jack-Up model were compared to the method stated in the SNAME Guidelines. Results showed the latter to be conservative due to the fact that aerodynamic interference is not incorporated into the calculation. The wind tunnel test results gave wind loads up to 30% lower than the projected area method. This study was extended by [Jiang et al.] who compared the wind tunnel experiment results with those obtained from a CFD simulation of the Jack-Up. Their conclusions were that CFD produces similar (but slightly higher) results as those generated from wind tunnel experiments. The difference in results ranged from 10 to 15%. This confirms the conservatism of the approach described in the SNAME Guidelines. The reasoning for a conservative wind calculation approach might originate from the fact that wind loads are statically calculated based on a 1-minute sustained wind speed. Effect of stronger gusts might be captured by applying a conservative calculation approach.

**Dynamic Response** and its prediction is the area that has enjoyed most attention of research mainly for two reasons:

- Jack-Ups show significant dynamic response due to the fact that their natural period for surge/sway direction is often close to that of high energy waves.
- Dynamic response is always the starting point for real-life measurement campaigns. Breakdown of the dynamic response can be used to estimate static loads on the structure.

FEM analyses and *in-situ* measurement campaigns are the two methods that have been used to study the dynamic response of Jack-Up rigs. A summary of the studies published in the last 25 years is given in Table 2-1 and Table 2-2:

**Table 2-1:** Overview of published FEM analysis: Ordered by publishing year, and grouped according to type of model (stick or detailed) and type of analysis (static, frequency domain or time domain)

			Λ	Iodel			Dynam	nic
Y ear	Author	$WD \ [m]$	Stick	Detailed	Dim.	Static	Frequency	Time
1986	Nagy	95	٠		3D		٠	•
1993	Tromans/vd Graaf	91.4		•	3D	•		
1998	Williams	90	٠		2D		•	•
1999	Cassidy	90	•		2D			•
1999	Williams	90	•		2D			•
2001	Cassidy	90	•		2D			•
2011	Cassidy	100	•		3D			•
2012	Mirzadehniasar/Cassidy	105		•	3D			•
2012	Cheng/Cassidy	91.4		•	3D	٠		

Table 2-2: Overview of North Sea measurement campaigns that all took place in the 90's.

Rig Name	Rig Type	Soil	$WD \ [m]$	$H_{max}[m]$	Dyn. Fixity [%]
Rowan Gorilla II	MLT 200-C	Sand + Clay	94	14	30
Kolskaya	GustoMSC	Sand	72	21	12
Galaxy-1	F&G L780 MOD VI	Sand	92	8	50
Galaxy-1	F&G L780 MOD VI	Silty sand	75	7.5	30
Galaxy-1	F&G L780 MOD VI	Clay	89	12	80-90
Magellan	F&G L780 MOD V	Clay	89	17.1	70-80
Magellan	F&G L780 MOD V	Silty sand	77	16.4	60-70
Monitor	F&G L780 MOD V	Sand	28	11	47-51
Monitor	F&G L780 MOD V	Sand + Silt	84	9	50
Maersk Endurer	BMC-350	Clay	91	21.6	59

The comparison between results obtained from measuring campaigns and those generated by computer models allows researchers to gain insight into the accuracy of the latter. Through the comparative studies summarised in the tables above the following conclusions were made:

- Dynamic Amplification Factors: DAFs measured on *in-situ* rigs were found to vary from values just above unity to more than two. This is significant for a bottom founded structure and was due to the fact that the natural periods of the rigs under investigation often had natural periods in surge/sway which were close to the periods of high energy waves.
- **Damping:** Energy dissipation values were also derived from the results of *in-situ* rigs. These values ranged from 2% for low sea-states to 5.5% for high sea-states. These values proved consistent for the different measurement campaigns as described in Table 2-2 and were derived from the bandwidth of the response spectrum.
- Soil Fixity: The percentage of soil fixity was also estimated from measurement campaigns as it plays a dominant role in the dynamic response analysis of Jack-Ups. Fixity values were found to vary significantly with soil conditions. Stiff sand resulted in high fixity ranging up to 80%, whereas soft clay lead to values as low as 20%. Soil fixity is defined as follows:

$$F(\%) = (f_m^2 - f_p^2) / (f_f^2 - f_p^2)$$
(2-1)

In which  $f_m$  is the actual natural frequency,  $f_p$  is the natural frequency for pinned condition and  $f_f$  for fixed condition.

Table 2-1 and Table 2-2 show that the dynamic response analysis of Jack-Ups has enjoyed a significant amount of attention since the publishing of the SNAME Guidelines. They also show that the water depths in the studies have remained limited to around 300' (91m), while the water depth limits of newly introduced designs have risen significantly since the change of the millennium. This discrepancy is shown in (Figure 2-1) and is a driver for this thesis:



Figure 2-1: Water depth limits of introduced Jack-Up designs and those studied in research.

### 2-2 Jack-Up Failure

Jack-Ups see relatively high failure rates when compared to fixed platforms [Leijten and Efthymiou, 1991]. Leijten and Efthymiou analysed accident data for both platform types over an interval of 20 years. The results of their findings are given in Table 2-3.

Table 2-3: Total loss accidents for Jack-Ups and Fixed Platforms during the 70's and the 80's.

	Number of	f Accidents	Per 10,000	Unit Years
	1970-79	1980-89	1970-79	1980-89
Fixed platform	7.3	1.1	1.7	0.5
Jack-Ups	162	97	35	34

The failure rates for Jack-Ups have remained high towards the end of the 19th century which was why the UK HSE watchdog published a report on foundation-related failures that occurred in 2004. Their publication included a research in published papers addressing failure modes and a case study of 55 foundation-related incident reports available in the public domain. The following failure modes were identified and discussed:

- **Punch Through:** The majority of foundation related failures involve punch-through of one of the spudcans. This failure mode is often found in locations were there is a (relatively weak) clay layer underlying a (relatively strong) sand layer. Although punch-throughs can lead to excessive damage to a rig, they are also often readily prevented by performing a thorough soil investigation prior to rig installation.
- Rack Phase Difference: Eccentric spudcan loading can result in a vertical difference in height between the chords within a leg. If this Rack Phase Difference (RPD) becomes excessive it may lad to buckling of the diagonal bracing in a leg. RPD can be caused by a variety of circumstances which are given below (Figure 2-2). They were identified by [Nowak and Lawson]:



Figure 2-2: RPD causes, from Left to Right: Sloping seabed, uneven seabed, scour, pre-existing footprints

RPD was found to occur more often with modern rig designs, reasons for which will be investigated and discussed later in this thesis.

#### **Rack Phase Difference**

The preceding section indicates the (increased) occurrence of RPD leading to possible Jack-Up failure. For this reason the topic has seen an increase of interest over the past decade or so. In 2003, [Stonor et al.] published a case study of the leg bracing damage that occurred on a F&G L780 MOD V rig design due to RPD. The rig had developed RPD over a period of three months during the winter of 2001-2002 which was caused by scour which resulted in additional leg settlement. During the third re-jacking operation braces in a leg section buckled and the rig had to be repaired at shore. [Tan et al., 2003] presented a computerengineering focused effort to model the development of RPD during jacking operations for a rig experiencing a 2.2 MN side-wind. A contact algorithm was incorporated into the analysis to mimic the behaviour of the guides during jacking. Leg loads were also given but the authors did not proceed to address stresses within the braces. The author concluded the report with the recommendation to perform jacking operations in mild environmental conditions. In 2005, [Nowak and Lawson] published a qualitative paper which introduced the growing RPD problem and its causes. Several RPD management methods were presented. No structural analysis of RPD was performed. Two years later, [Nowak et al.] published a more industry related paper which continued to focus on RPD. Several industry solutions were presented including automatic RPD monitoring systems and independent chord jacking capability.

All of the above studies on RPD conclude that it has become more problematic in recent years with newer rig designs. This trend will be further investigated in the next chapters and will remain a topic of discussion throughout this thesis.

# 3

## **Market Analysis**

## 3-1 History of Jack-Up Design

The first Jack-Up to be employed in the offshore oil- and gas industry was the 12-legged GUS-I built in 1954 by the LeTourneau company, an engineering and construction company specialized is the design of earthmoving machinery. The rather awkward design, employing a large number of cylindrical legs, was quickly followed by a lattice-leg Jack-Up which has close resemblance to the vast majority of Jack-Ups designs used nowadays. They are shown in Figure 3-1 and Figure 3-2:



**Figure 3-1:** GUS-I, the first Jack-Up to be used in offshore drilling activities



**Figure 3-2:** The Scorpion, the first Jack-Up to use truss-legs

With the surging oil demand due to American prosperity after WWII the development of the Gulf of Mexico in terms of oil production grew rapidly. This growth was accompanied by developments in the Jack-Up market where the triangular three lattice-leg design was rebuilt and improved by LeTourneau. The development of the North Sea started to take shape in the 1970's which was accompanied by a further growth in need for MODU units like Jack-Ups. More companies were offering rig designs in order to take a share in the growing MODU market. As the reserves in both GoM and the North Sea started declining towards the end of the 90's the industry was pushed to greater water depths and harsher environments. This called for the latest generation of MODU Jack-Up designs, specially designed for deep water harsh environment applications.

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The list of Jack-Up designs that were introduced over the last 60 years is long and confusing at first sight. Rigs are named by type but are also given names similar to those given to ships when they are launched. Rig types are iterated according to the different classification standards used by different countries in the oil- and gas industry. Extending leg length or changing the spudcan of a rig can also change the type name of a rig which leads to a large variety of designs which are actually very similar. A study on the history of major Jack-Up designs reveals that some designs are actually copied as designer companies buy design rights from their competitors in order to set foot in the MODU Jack-Up market. An overview of major designs is given according to the decades they were introduced:

#### 1970's

With the offshore drilling market booming LeTourneau introduced the famous **MLT-116C** design towards the end of the 70's. This three, square legged design was to become the industry workhorse in the Gulf of Mexico and has remained popular ever since. Other companies like GustoMSC were also producing Jack-Up designs but were less successful in doing so, reasons for which are not clear.

#### 1980's

As the demand for Jack-Ups kept rising, more design companies started to offer rig designs during the 80's. Friede & Goldman introduced their F&G-L780 design which used a triangular (3 chord) leg design in contrary to the square leg design used by LeTourneau. The F&G-L780 quickly became a major competitor to the LeTourneau design and has also been used extensively in the Gulf of Mexico. GustoMSC re-entered the Jack-Up design market with their extremely successful **CJ-series** which were the first Jack-Ups to employ cantilevered drilling derricks, extending the use of rig designs. The inclusion of a cantilevered derrick also allowed Jack-Ups to do something semi-subs and drill-ships could never do, with a derrick extending over an existing platform to perform drilling operations. All Jack-Up designs would soon be equipped with cantilevers.

#### 1990's

In 1994 LeTourneau was taken over by Rowan, a drilling operator, which meant a rig designer and rig operator were now combined into one company. For this reason new designs created by the LeTourneau team were now called *Gorilla's* and *Tarzan's* according to Rowan's naming policy. LeTourneau designs with their square legs continued to be used and developed at Rowan to this date. Keppel FELS also entered the lucrative Jack-Up design market and bought the F&G L780 MOD V and MOD VI design rights in 1997 and used these to develop its own rig designs. For this reason some KFELS rig designs still carry MOD V in their name to indicate their F&G heritage.

#### 2000's

The turn of the millennium was accompanied by a new generation of Jack-Ups called the 'ultra-premium harsh environment' designs. These rigs allowed for both deep water and harsh environments enabling oil companies to drill all year round in challenging locations. The new designs also have premium capabilities in terms of available power on board and allowable variable load to enable deeper wells to be drilled. Rowan (LeTourneau) introduced the **200C Gorilla** and **219C Super Gorilla**, F&G introduced the **F&G JU2000E** and KFELS introduced the **KFELS B Class**, the **KFELS Super N Class** and the **KFELS Super A Class**.

An overview of major designs introduced over the past fourty years is given on the next page.

2010's	Gorilla XI.		Super A-Class	C180	Pacific 400
00's	116-E 240C EXL	Super M2	Super N-Class		
200	225 Tarzan	JU2000E JU2000A	B-Class Super B-Class	CJ70	Pacific 375
)'s	219-C		A-Class		
8		M2		CJ62	
)'s		L-780 MOD V		CJ50	
8(	200-C	L-780 MOD II L-780 MOD II		CJ46	
0's	116-C				
Z	LeTourneau	F&G	KFELS	GustoMSC	BMC



3-1 History of Jack-Up Design

## 3-2 Introduction to Jack-Up design

The Jack-Up structure was briefly described in the first chapter of this thesis. A more detailed explanation is given below in Figure 3-4. Although different designs exist most (modern) Jack-Ups share the following features:



Figure 3-4: General overview of a Jack-Up and its components

The **drilling derrick** is supported by the **hull** which also holds room for accommodation variable load. It is connected to the **legs** at the **jacking houses**. These hold the components that form the leg-hull connection and allow for jacking of the structure. **Guides** prevent rotation of the legs during jacking, during which the **pinions** drive the legs vertically through the hull. When the required jacking height is achieved, **rack chocks**, engage with the **chords** of the legs and form a rigid connection. The chords within a leg are connected by **braces**. Finally, the **spudcans** are attached to the lower ends of the legs and penetrate into the soil to form the foundation of the structure.

The top view of a typical Jack-Up is given in Figure 3-5. The three legs form a triangle within the hull. A **transverse** and **longitudinal leg spacing** are used to indicate the distances between the legs. Due to their hybrid nature, Jack-Ups can float. For this reason they have a **stern** which is often the side where the derrick is located and a **bow** where the accommodation and helipad are situated. The same heading convention as in ships is used, where a  $0^{\circ}$  heading indicates head on waves.



Figure 3-5: Jack-Up top view and heading convention

## 3-3 Market Analysis

The design parameters of all major Jack-Up designs are given in a database which is shown in Table 3-1 and Table 3-2. This information is used to identify trends in the design of Jack-Ups. The analysis results in the following flow chart that summarizes design problems that arise when rigs are used in deeper water and harsh environments. The flowchart also identifies the solutions designers apply to counteract the arising problems:



Figure 3-6: Flow chart of the design solutions applied to deep water harsh environment rigs

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

Table 3-1: Main characteristics of all Jack-Up designs - Part 1

T. Koole

Table 3-2: Main characteristics of all Jack-Up designs - Part 2

T. Koole

Several trends can be identified from the tables on the preceding pages:

#### **Leg-Hull Connection**

The leg to hull connection in a Jack-Up is designed to transfer the axial loads, bending loads and shear forces from the hull to the leg and vice versa. Pre 90's Jack-Up designs used guides to account for the shear force and bending moment on the leg whilst using relatively flexible pinions to transfer the axial load that is caused mostly by the weight of the hull and its variable load. The guides apply a shear force on the leg structure which is constrained in the hull. This requires a leg with heavy bracing to be able to withstand this shearing action. GustoMSC designed and patented the leg fixation system in the early 1980's. Using rack chocks which engage into the teeth of the chords, a rigid connection is made between the leg and the full. Due to its rigidity, the system takes over much of the workload from the upper and lower guides but now directing the bending moment straight into the chords in the form of a vertical couple. This allows rig designers to use relatively slender bracing which in turn reduces hydrodynamic loads and therefore allows the Jack-Ups to be designed for deeper water at harsh conditions. Figure 3-7 and Figure 3-8 give a graphical representation of the old connection system and the newer design which uses rack chocks.



Figure 3-7: Old connection design

Figure 3-8: New connection design

All modern Jack-Up designs use rack chocks as a method of leg-hull connection when the rig is in elevated condition. The consequent possibility of using (relatively) slender bracing is also seen in these designs.

#### Leg Design

The leg design of a Jack-Up might be the most important aspect of the rig design (in elevated condition) as it dictates not only hydrodynamic loading, but also plays a very important role in the dynamic response of the structure. Jack-Up truss legs consist of three or four chords that are interconnected by horizontal and diagonal braces. As mentioned in the previous paragraph, the introduction of rack chocks has allowed for more slender legs to be designed. This is a necessary step in order to allow rigs to be employed in harsh environments such as the North Sea. The change in leg design can be seen by comparing three different leg design by one of the leading Jack-Up designers, Friede & Goldman. Figure 3-9 shows three subsequent leg designs with the most recent on the right, and the oldest on the left. The image is drawn to scale and shows how chord spacing has increased over the years.



Figure 3-9: Side view of leg designs increasing with most recent on the right

The bracing type (K-bracing, X-bracing and split-X bracing) has also changed as rig designs developed. Older LeTourneau and F&G rigs used K-bracing which results in legs that are able to withstand large shear but are also heavy and have increased bracing exposed to hydrodynamic loads. All modern deep water harsh environment Jack-Up designs employ (split) X-bracing as these allow for a stiff but spacious leg that attracts minimal hydrodynamic loads. More detailed analysis of leg designs is covered in Chapter 4.

#### Leg Spacing

As Jack-Ups shift to deeper waters a larger leg spacing is required to provide resistance to increasing overturning moment. This trend is found in Jack-Up designs. The relationship between the transverse and longitudinal leg spacing (see Figure 3-5) is very consistent throughout the different designers and types, with the 3 legs forming an equilateral triangle. The longitudinal leg spacing is therefore found by multiplying the transverse leg spacing by a factor  $\sqrt{3}/2$ .

The leg spacing to maximum water depth ratio for the listed designs has been calculated and is found to be relatively constant. With a mean of 2.65 and a 0.26 standard deviation the Relative Standard Deviation (RSD) is 10.0%. This ratio will be higher for harsh environment Jack-Ups since the required resistance to overturning moments has increased. The results for all 32 rig designs are summarized in the following histogram (Figure 3-10):



**Figure 3-10:** Histogram showing ratio of max water depth to leg spacing for all Jack-Up designs incorporated into the market analysis.

A closer look at the individual ratios shows that older (pre millennium) Jack-Ups tend to use WD to leg spacing ratios close to or slightly below three. For Modern Jack-Up that are designed to operate in harsher conditions as well as deeper waters this ratio has decreased and approaches a value of two. This is in line with the flowchart in Figure 3-6, harsher conditions and deeper waters lead to increased leg spacing in order to increase the overturning moment resistance of the rig.

## 4

## **Quasi-Statics**

*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 (BSH) (total lateral forces) and an Overturning Moment (OTM). 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 4-1 shows the general loads on a Jack-Up in elevated condition.



Figure 4-1: 2D representation of environmental, gravitational and (resulting) foundation loads.

### 4-1 Wind Loads

Wind is caused by differences in atmospheric pressure. These pressure gradients originate from temperature differences and the rotation of the earth. The moving air particles collide with all parts of the Jack-Up that extend above the water surface. The deceleration of the air particles causes wind loads to act on the structure.

#### 4-1-1 Calculation

In the assessment of Jack-Ups the wind load is modelled as a static force. The reasoning behind this is that the period of oscillation for wind gusts (30 to 300s) is considerably higher than the natural periods of Jack-Ups (<10s). For this reason relatively simple calculations suffice to estimate the wind loads on the structure.

SNAME recommends use of the projected area method in which the wind loads on the Jack-Up are calculated by dividing the exposed areas into blocks. Each block is given a height coefficient  $C_h$  and a shape coefficient  $C_s$ . These coefficients are used to calculate the wind load on each separate block. The total wind load on the Jack-Up is then calculated by summation of the individual block loads:

$$F_{WIND} = \sum_{i=1}^{n} P_i A_i \tag{4-1}$$

In which  $P_i$  is given by:

$$P_{i} = \frac{1}{2}\rho(v_{ref})^{2}C_{h}C_{s}$$
(4-2)

The summation of all the exposed areas multiplied with their height and shape coefficients gives the total wind area of a Jack-Up. This number can readily be multiplied by  $1/2\rho v_{ref}^2$  to give the final wind load. The velocity profile of the wind is defined by the 1 minute mean wind velocity at 10 m above sea-level and varies according to height. To find the wind velocity at height z, the following relationship is used:

$$v_z = v_{ref} (\frac{z}{z_{ref}})^{0.1}$$
(4-3)

The profile given by Eq. (4-3) generates a velocity profile where  $v_z = v_{ref}$  at 10 meters above sea-level and  $v_z$  asymptotically tends to 1.2 for  $v_z >> v_{ref}$ . Since Jack-Ups will use airgaps of at least 15 meters the velocity profile can be assumed constant with a magnitude of  $1.1 \times v_{ref}$ . The calculated wind load is multiplied by a safety factor of 1.15 to give the factored environmental load due to wind.
#### 4-1-2 Trends for Deeper Waters

Chapter 3 has shown leg spacing and therefore hull size increases as Jack-Ups are designed for deeper waters. This results in larger surface areas exposed to the incoming wind flow which increases loads accordingly. To understand the magnitude of this increase a comparison between the projected areas of four common rig designs is shown in Figure 4-2.



**Figure 4-2:** Wind areas for common rig designs: With increasing water depth capacity (from left to right), the wind areas of the structures (excluding legs) increase accordingly.

#### 4-1-3 Typical Values for Modern Jack-Ups

The wind areas in Figure 4-2 can be combined with Eq. (4-2) to give estimates of the total wind loads on the different Jack-Ups. Here the velocity profile is captured by a factor 1.1 as described in the previous section. With the addition of a 1.15 safety factor the total factored wind load is then found according to:

$$F_{WIND} \approx SF \cdot \frac{1}{2} \rho (1.1 \cdot v_{ref})^2 A_{total}$$
(4-4)

$$F_{WIND} \approx 0.85 \cdot v_{ref}^2 \cdot A_{total} \tag{4-5}$$

The resulting wind loads for the four Jack-Up designs considered are given in Figure 4-3.



Figure 4-3: Factored wind loads for common rig designs and different wind speeds

The results from Figure 4-3 can be used to estimate the OTM for these rigs in different water depths and wind speeds. The OTM due to wind loads can be estimated by multiplying the total wind load, given by Eq. (4-5), with the center of effort for the load:

$$OTM_{WIND} = F_{WIND} \cdot CoE \tag{4-6}$$

The CoE for wind loads on Jack-Ups is the summation of the water depth, the penetration, the airgap and finally the hull height. We assume WD + 40 for the sake of estimating the OTM. The resulting equation is given below:

$$OTM_{WIND} = F_{WIND} \cdot (WD + 40) \tag{4-7}$$

 Table 4-1: Factored OTM [MNm] due to wind loads for common Jack-Up designs. Rounded to nearest 5 MNm

	WD = 100		И	WD = 125			WD = 150		
Wind Speed [m/s]:	30	40	50	30	40	50	30	40	50
F& G MOD II	180	320	495	210	375	585	245	430	675
CJ46-X100D	225	400	625	265	470	735	305	540	845
KFLES B-Class	240	425	665	280	500	785	325	580	905
F& GJU2000E	355	635	990	420	750	1170	485	860	1345

Figure 4-3 illustrates the effect of designing Jack-Ups for deeper water. Deeper water rigs tend to become bigger which exposes a larger surface area to the incoming wind profile. Wind loads therefore increase proportionally. This effect will be enhanced even further with regards to the resulting OTM as the water depth raises the wind centre of effort. For completeness of wind load calculation the leg sections that protrude out of the sea are also to be taken into account. For this study however, the remaining leg length is assumed to be small as the Jack-Ups are pushed to their limits in terms of water depth (and will therefore have little leg length remaining). The wind loads on the legs are also considerably lower than those compared to the hull and its superstructure due to the relatively small diameters of the chords and braces.

# 4-2 Wave and Current Loads

Hydrodynamic loads act only on the Jack-Up legs. The airgap is chosen such that the 50year return design wave will not hit the hull. A safety margin of 1.5m is added to prevent wave-in-deck situations from occurring. Shell uses additional criteria to select the airgap.

The Jack-Up legs are truss-structured and are made up of chords and braces which have relatively small diameters compared to the wavelength of incoming design waves. For this reason the use of theory for slender cylinders to calculate hydrodynamic loads is valid.

#### 4-2-1 Calculation

The hydrodynamic forces on slender cylinders comprise of a (linear) inertia component and a (non-linear) drag component that act in the same direction as the flow.

Morison (1950) assumed the hydrodynamic loading to be a superposition of the two which leads to the well-known Morison's equation Eq. (4-8).

$$F(t) = \frac{\pi}{4}\rho C_m D^2 u'(t) + \frac{1}{2}\rho C_D u(t)|u(t)|$$
(4-8)

One of the two terms (inertia or drag) is often found to be dominant when calculating hydrodynamic loads using Morison's equation. This dominance can be predicted by calculating the Keulagan-Carpenter (KC) number KC. It is defined as:

$$KC = \frac{VT}{L} \tag{4-9}$$

In which V is the amplitude of the flow velocity, T is the period of oscillation and L is the diameter of the cylinder in question.

For Jack-Ups in storm condition both V and T increase while the diameter of the truss members is relatively small. This results in high KC values and therefore a drag dominated load. This is a generally accepted statement in the hydrodynamic load calculation of Jack-Ups.

#### Velocity profile

The velocity profile of the water particles, which is used in Morison's equatio,n consists of a superposition of the wave induced velocity profile and the current velocity profile. The first is calculated using one of several available wave theories. Although multiple wave theories exist, the two theories relevant for water depths > 100m include Airy wave theory and Stokes 5th order wave theory. Wheeler stretching can be applied to the Airy wave theory to improve accurateness. The current velocity profile is simply superimposed onto the wave velocity profile to give water particle velocities (and accelerations) across the depth profile.

A brief study was performed to quantify the statements above. A simple pile was modelled in USFOS and waves were run through using different wave theories:

	$H_{max} = 10$	$H_{max} = 15$	$H_{max} = 20$
	$T_{ass} = 10$	$T_{ass} = 12.5$	$T_{ass} = 15$
Airy, extrapolated	2.47E + 00	$3.90E{+}00$	6.02E + 00
Airy, stretched	$2.40E{+}00$	3.38E + 00	5.42E + 00
Stoke's $5$ th	$2.46E{+}00$	$3.83E{+}00$	$8.41E{+}00$

Table 4-2: Wave loads for different wave theories on single pile model

The results from Table 4-2 prove the (common knowledge) that airy wave theory can be used for waves that are relatively small compared to the water depth (H/d < 0.1) and for which the water depth to wave length ratio is large (>0.5). This is the case for the results in the first column of the table. The differences in calculated wave do not vary significantly between the different wave theories used. When the H/d and d/L decrease the calculated wave loads start to vary significantly. The following figure can be used to decide on which wave theory is to be sued for the analysis (Figure 4-4):



**Figure 4-4:** Graph for selection of appropriate wave theory for a given wave height h, wave length L and water depth d.

#### Wave Kinematic Reduction Factor

Two-dimensional wave theory overestimates the kinematics of real 3D ocean waves. In reallife wave spreading occurs as not all water particles move in the same direction. This wave spreading is incorporated into the analysis by reducing the kinematic profile by 0.86.

#### 4-2-2 Modelling of the Leg

SNAME recommends two different methods for calculating W/C loads on the truss legs:

- Detailed Leg Model: Gives a full description of the leg geometry. Values for C<sub>d</sub> and C<sub>m</sub> are chosen according to model tests or calibrated against measured data. The large number of elements in each leg results in excessive calculation time required to calculate the W/C loads along the structure.
- Equivalent Leg Model: Simplifies the model by replacing the detailed truss structure with an equivalent beam at the geometric centre of the leg. Its diameter and values for C<sub>d</sub> and C<sub>m</sub> are chosen to match the W/C loads of the detailed truss structure in consideration.

The reduction in computational time when using an equivalent leg model instead of a detailed leg model is significant. When using the detailed leg model, each bay consists of approximately 20 elements. Each leg consists of roughly 15 bays which means all three legs require almost 1000 elements to be modelled. The simplified leg model allows modelling using a single element for each bay and therefore reduces the computational time drastically.

#### Benchmark

The procedure used by SNAME to obtain the equivalent diameter  $D_e$  and accompanying hydrodynamic coefficient  $C_{D_e}$  and  $C_{M_e}$  involves summation of the individual chords and braces that make up the truss structure. An example calculation used to find the equivalent hydrodynamic properties for the F&G JU2000E leg design can be found in Appendix A. For this leg design the hydrodynamic loads of the detailed model were compared to the loads for an equivalent model. The results of the benchmark are given in Table 4-3:

**Table 4-3:** Comparison of waveloads on detailed model with equivalent model. Both models were exposed to 12m regular wave and maximum wave load noted

	Detailed	Simplified
Diameter [m]	Various	1.48
$C_D$	1.0	3.09
$C_M$	1.8	2.0
Total Load [N]	3.43 E5	4.09 E5

The difference in wave loading is approximately 19% which is quite significant. The equivalent leg procedure is based on wind-tunnel results of actual truss leg sections. USFOS might underestimate the hydrodynamic loading on the detailed leg design, reasons for which are unclear.



Figure 4-5: Detailed leg model



Figure 4-6: Simplified leg model

# 4-2-3 Hydrodynamic Loads on Modern Jack-Ups

The equivalent leg properties were calculated for a number of different leg designs of which chord and brace diameters were known. The results are given in the following table. The results are ordered in terms of increasing rig size (and water depth capabilities).

**Table 4-4:** Hydrodynamic Parameters for different rig designs, increasing in size from top to bottom

Rig Design	$D_e$	$C_{D_e}$	$D_e * C_D$	$C_{A_e}$	$A_e$
F&G MOD II	1.22	2.98	3.64	2.00	1.29
F&G MOD V	1.33	2.70	4.01	2.00	1.96
KFELS B Class	1.42	3.18	4.52	2.00	1.79
F&G JU2000E	1.48	3.09	4.59	2.00	1.73
Gusto CJ62	1.74	3.11	5.35	2.00	2.73

The  $D_e * C_D$  coefficient increases from 3.64 for the F&G MOD II design to 5.35 for the CJ62 design. This is due to the increase in chord spacing which results in longer braces. Since the wave loads on Jack-Ups are drag dominated, the  $D_e * C_D$  is dominant in the wave load calculation. The parameters in the table above can be used in the following section to estimate wave loads on different Jack-Up designs.

#### Wave Loads

The parameters from Table 4-4 can be used to calculate wave loads on typical (deepwater) Jack-Ups. The calculations were done in USFOS using Stokes 5th order wave theory. The results for different water depths, wave heights and wave periods are given in Table 4-5 and Table 4-6:

Table 4-5: Factored wave loads [in MN] for different leg designs and wave conditions at 100m WD  $\,$ 

	$H_{max} = 15 \mathrm{m}$				$H_{max} = 20\mathrm{m}$				$H_{max} = 25 \mathrm{m}$			
	$T_{ass}$	= 10s	$T_{ass}$	= 15s	$T_{ass}$	= 10s	$T_{ass}$	= 15s	$T_{ass}$	= 10s	$T_{ass}$	= 15s
	BSH	OTM	BSH	OTM	BSH	OTM	BSH	OTM	BSH	OTM	BSH	OTM
F&G MOD II	1.9	180	1.6	130	3.9	380	3.1	255	7.3	725	5.2	450
F&G MOD V	2.2	205	1.8	145	4.5	430	3.4	280	8.2	810	5.7	490
KFELS B Cl.	2.4	225	2.0	160	4.9	470	3.8	315	9.1	900	6.4	550
F&G JU2000E	2.3	215	1.9	155	4.7	460	3.7	310	8.8	875	6.2	535
Gusto CJ62	2.1	200	2.0	160	4.5	435	3.7	310	8.4	835	6.3	545

Table 4-6: Factored wave loads [in MN] for different leg designs and wave conditions at 150m WD  $\,$ 

	$H_{max} = 15 \mathrm{m}$				$H_{max} = 20 \mathrm{m}$				$H_{max} = 25 \mathrm{m}$			
	$T_{ass}$	= 10s	$T_{ass}$	= 15s	$T_{ass}$	= 10s	$T_{ass}$	= 15s	$T_{ass}$	= 10s	$T_{ass}$	= 15s
	BSH	OTM	BSH	OTM	BSH	OTM	BSH	OTM	BSH	OTM	BSH	OTM
F&G MOD II	1.9	275	1.6	210	3.9	575	3.1	410	7.3	1090	5.3	715
F&G MOD V	2.2	315	1.8	235	4.5	655	3.5	450	8.2	1225	5.8	778
KFELS B Cl.	2.4	345	2.0	260	4.9	720	3.8	505	9.1	1350	6.5	870
F&G JU2000E	2.3	330	2.0	254	4.7	695	3.8	495	8.8	1315	6.3	850
Gusto CJ62	2.1	310	2.0	260	4.5	660	3.8	500	8.4	1250	6.4	865

Several trends can be identified from the tables above:

- Leg Spacing: Due to leg spacing there is a phase difference between the wave loads at individual legs. For 0° heading two legs encounter a wave crest simultaneously while the force at the remaining leg is less. This effect is enhanced for waves with higher period and rig designs with large leg spacing (like the CJ62). Although this rig design has the highest values for  $D_e$ ,  $C_{De}$  and  $A_e$  its hydrodynamic loads due to wave forces are found to be similar or less then smaller rigs because the leg spacing increases the phase difference and therefore total quasi-static maximum wave load on the legs.
- Water Depth: Increasing water depth from 100m to 150m has a negligible effect on the total horizontal hydrodynamic wave loads. The reason for this is that most of the wave loads act on the upper part of the submerged legs. The wave kinematics profile decreases exponentially with depth and has little energy as the depth passes 30 to 50

m. The OTM however, increases linearly with water depth simply because the center of effort for the wave loading increases for increasing water depth.

• **CoE:** The center of effort for wave loads can be found by dividing the OTM by the BSH. For the results in the tables above we find that the CoE for wave loads lies at around 90-95% of the total height of the water column.

#### **Current Loads**

Hydrodynamic loads due to current have been calculated separately in order to maintain insight into the origin of the different environmental loads. Table 4-7 shows hydrodynamic loads due to current in a similar way as in the previous section. Current speeds up to 1.5 m/s have been considered. The velocity profile is assumed constant over depth.

**Table 4-7:** Factored loads due to currents for different rig designs, water depths and current speeds.

		WD = 100					WD = 150					
	<i>v<sub>c</sub></i> =	= 0.5	$v_c =$	= 1.0	$v_c =$	= 1.5	$v_c =$	= 0.5	$v_c =$	= 1.0	$v_c =$	= 1.5
	BSH	OTM	BSH	OTM	BSH	OTM	BSH	OTM	BSH	OTM	BSH	OTM
F&G MOD II	0.2	8	0.6	32	1.5	72	0.2	18	1.0	72	2.2	163
F&G MOD V	0.2	8	0.6	32	1.4	72	0.2	18	1.0	71	2.1	161
KFELS B Cl.	0.2	10	0.8	40	1.8	90	0.3	22	1.2	90	2.7	202
F&G JU2000E	0.2	10	0.8	40	1.8	91	0.3	23	1.2	91	2.7	205
Gusto CJ62	0.2	12	1.0	48	2.2	108	0.4	27	1.4	108	3.2	242

The results in the table above were generated under the assumption that the current velocity profile was constant over the entire length of the water column. This is however not the case in reality. The current velocity profile reduces with depth which means the values in the table above include an overestimation both in BSH and OTM. The values of tables Table 4-5, Table 4-6 and Table 4-7 show that wave loads are the dominant hydrodynamic load for most situations both in terms of BSH and OTM.

# 4-3 Resistance

The ability of a structure to withstand the loading it is exposed to is called its resistance. Jack-Ups have a number of global and local failure modes which limit their resistance in different storm headings. After the environmental loads have been determined and the dynamic response is included into the analysis, the following checks are performed in the SSA:

 1. Overturning Stability

 2. Preload Capacity

 3. Bearing Capacity

 4. Leg Sliding

 5. Leg Chord Strength

 6. Leg Brace Strength

 7. Chock Holding System

The first four UC's can be considered global as they do not require a detailed structural model of the Jack-Up, but can be assessed using the reaction forces at the foundation interface. They are shown in Figure 4-7. The bottom three UC's require a more detailed structural model and will therefore not be considered in this thesis.



Figure 4-7: Preload/Bearing Capacity (left) and Overturning Stability failure modes (right)

#### 4-3-1 Overturning Stability

The minimum overturning stability of 3 legged Jack-Up designs occurs for  $0/120/240^{\circ}$  weather heading. The environmental loads cause an OTM about the axis that connect the spudcan of the aft legs. If this OTM is too big, the windward leg will lift vertically off the ground (or slide) which leads to failure of the structure.

The overturning stability in this heading can be estimated using the following relation:

$$R_{OTM} = \frac{CoG_x}{3} \cdot m_{hull} \cdot g \tag{4-10}$$

An additional overturning stability can be included by taking into account the fixity of the aft spudcans. For sake of estimating OTM resistance, this is not incorporated in the following results.

Fable 4-8: OTM	resistance [MNm	for different	Jack-Up designs (	(excluding foundation	ı fixity)
----------------	-----------------	---------------	-------------------	-----------------------	-----------

	$CoG_x/3$	$m_{hull}$	$R_{OTM}$
F&G MOD II	11.7	5500	630
KFELS B Class	13	8600	1095
F&G JU2000E	15.2	13300	1985
Gusto CJ $62$	18	18000	3180

#### 4-3-2 Preload and Bearing Capacity

Preload and bearing capacity are closely related as they both dictate the limit in allowable axial load of a spudcan into the soil. Breach of the preload or bearing capacity can cause punch-through of one or more spudcans. The critical weather heading for this type of failure is 60, 180, or 240 degree heading. Two legs align to form a neutral axis. The remaining leg is under high axial load due to the OTM caused by environmental loads.

Whether the maximum axial spudcan load is bound by preload capacity or bearing capacity depends on rig design and soil conditions. Modern rigs have high preload capacities to make them suitable for harsh conditions. Therefore the bearing capacity for the soil is more likely to limit maximum allowable axial leg load. This is especially the case for spudcans in clay as the bearing capacity is significantly smaller when compared to sand layers.

#### **Ultimate Bearing Capacity**

The ultimate bearing capacities of a spudcan foundation on sand and a spudcan foundation on clay are given in Eq. (4-11) and Eq. (4-12) respectively:

$$F_{v_{sand}} = (0.5\gamma' B N_{\gamma} s_{\gamma} d_{\gamma} + p'_0 N_q s_q d_q) A \tag{4-11}$$

$$F_{v_{clay}} = (c_u N_c s_c d_c + p'_0) A$$
(4-12)

In which B indicates the effective spudcan diameter, A its area, and N, s, and d are the bearing capacity factor, the bearing capacity shape factor and the bearing capacity depth factor respectively. The vertical bearing capacity for sand is dominated by the internal angle of friction  $\phi$  of the soil. This ranges from 20-40° for loose to dense sands respectively. The vertical bearing capacity for clay is dominated by the undrained shear strength  $c_u$  of the soil. This value ranges from 20-150 KPa for soft to stiff clays respectively.

Although these equations only indicate the upper limit for a purely vertically loaded foundation, they can give a clear understanding of the limits in ultimate bearing capacity of different spudcan diameters in different soils. The results for four different rig designs and six soil types are given in the following table:

			Sand		Clay			
	$D_{spud}$ [m]	Loose	Medium	Dense	$\operatorname{Soft}$	Medium	$\operatorname{Stiff}$	
F&G MOD II	11.9	25	75	280	35	60	150	
KFELS B Class	14	40	120	440	50	85	205	
F&G JU2000E	18	75	240	885	80	135	320	
Gusto $CJ62$	20	100	320	1190	95	165	390	

 Table 4-9: Ultimate vertical bearing capacity [MN] of spudcan foundation for different rig designs and soil conditions

The limited capacity of clay soils to form a good foundation under a spudcan is clearly shown in the results. The F&G JU2000E spudcan has more bearing capacity in a medium sand compared to the bearing capacity of a larger Gusto CJ62 spudcan in a medium clay. This effect reduces for larger penetrations in clay layers. This implies that Jack-Ups in clay foundations will tend to fail in a mode where the bearing capacity of the foundation is the limiting factor. Failure due to lack of overturning moment is more likely to be a dominant failure mode in situations where the foundation consists of sand due to its increased bearing capacity.

Table 4-9 also clearly shows the importance of obtaining the correct soil properties for a given site. The difference between the ultimate vertical bearing capacity of a loose sand versus a dense sand is very large which will drastically affect the resistance of a Jack-Up in a location. 5

# **Dynamics - Approach**

Modern MODU Jack-Ups consist of a relatively short, rigid hull supported by relatively long, flexible legs which enables them to operate in water depths exceeding 100 meters. This often results in a natural period  $T_n$  which is in the same range as the periods of high energy waves  $T_p$ . This can lead to resonance which significantly increases the loading on the structure. This chapter presents the dynamic response analysis of modern Jack-Ups.

# 5-1 Inertial Load Set

The goal of the dynamic response analysis is to determine the amplification of the harmonic wave loads due to the inclusion of inertia. This amplification is given as a Dynamic Amplification Factor (DAF), which can be incorporated into a quasi-static analysis as an Inertial Load-Set. For fixed structures like Jack-Ups, a DAF is obtained for BSH and OTM.

These factors are then applied to the incoming wave loads to mimic the effect of inertial forces. Since  $DAF_{BSH}$  and  $DAF_{OTM}$  differ in value two different approaches can be used to produce the inertial load-set:

- Single point force: Use a single load applied at deck level to match the increase in OTM due to dynamic response. This will lead to an excess in BSH since the DAFs for the two will differ which should be incorporated into any final conclusions made.
- **Distributed load-set:** In the distributed load-set approach the dynamic response is modelled as a set of loads instead of a single load. This will more accurately mimic the effect of dynamic response as it takes into account the mode shapes of vibration. It also allows for matching both the DAF for BSH and for OTM.

# 5-2 Types of Dynamic Response Analysis methods

Different methods are used to determine the dynamic response of a system. Three methods are described below of which one is chosen for the method used to determine the dynamic response of Jack-Ups.

# 5-2-1 SDOF Approach

The Single Degree of Freedom (SDOF) approach uses single degree of freedom analogy to determine values for DAF. The structure is modelled as a classical mass-spring-damper system with one degree of freedom. DAFs can be calculated directly from the mass, damping and stiffness terms in the system. The SDOF method simplifies the dynamic system. This leads to the following errors in case of Jack-Ups:

• Linearised Stiffness: The assumption of SDOF analogy is accompanied by using a linear spring. This implies the stiffness of the structure can be modelled by a linear spring. Mainly due to so-called p-delta effects a Jack-Up has a non-linear stiffness in the directions of the first modes of vibration. P-delta effects occur in situations where a relatively slender axially loaded member deflects horizontally, as shown in Figure 5-1. The induced moment further enhances the deflection. This phenomena is seen in Jack-Ups due to the combination of a heavy hull mass supported by relatively long, slender legs:



Figure 5-1: P-delta effect in slender members in axial compression

• **Concentrated Mass:** SDOF analogy assumes a single point mass to capture the weight of the structure. In reality the mass of a Jack-Up is distributed and especially the mass and added mass associated with the Jack-Up legs will not be represented in the SDOF analogy. Concentrating all mass at the hull will artificially increase the rig natural period.

• Center of Effort: The SDOF approach assumes a single loading point. This can be accurate for mono-piles but due to the spacing of the Jack-Up legs the hydrodynamic loads on the different legs will have phase differences. This effect is enhanced for deep water Jack-Ups as they use larger leg spacing to increase OTM resistance. This can both potentially increase or decrease the DAFs found due to either reinforcement or cancellation behaviour due to the leg spacing.

# 5-2-2 Frequency Domain Analysis

The frequency domain method involves linearisation of the model and its loading before being solved deterministically. It allows the user to visually see how the dynamic response is generated due to the use of response spectra. Frequency domain analysis is powerful in this sense but is not suitable for Jack-Up analysis due to the following inherent non-linearities:

• Hydrodynamic Drag: Modelling of the hydrodynamic load on the truss legs is done using Morison's equation. The drag term varies non-linearly and therefore introduces a problem when performing frequency domain analysis. Jack-Ups are drag dominated in terms of hydrodynamic loading (high KC value) which enhances the effect of the error introduced when using frequency domain analysis. The effect of non-linear drag loading has been widely investigated, e.g. Borgman (1969), Pierson and Holmes (1965) and Hagemijer (1989). Figure 5-2 and Figure 5-3 [Baltrop and Adams, 1991] show how drag-dominated structures deviate from a linear (Gaussian) probability distribution due to the non-linearity of drag loading.

An additional effect of drag loading is the introduction of harmonics into the forcing. The drag loading in Morison's equation consists of a v|v| term which has a time history proportional to  $cos(2\pi ft) \times |cos(2\pi ft)|$ . This has a Fourier harmonic component at 3f (and higher, odd harmonics 5f, 7f etc.) which can potentially excite the system at higher frequencies (or lower periods). This is illustrated in Figure 5-4 which shows the force spectra calculated for a drag dominated member:

• **Structural Stiffness:** Similar to the SDOF method, the non-linearities in the structural stiffness of the system also pose a problem to the frequency domain method.

# 5-2-3 Time Domain FEM Analysis

The last method described for the dynamic response analysis is the Time Domain Finite Element Method (FEM) method. It allows for a complete description of the structure and its non-linearities. A stationary stochastic sea state is generated by superposition of (Airy) wave components and is 'run' through a finite element model in discrete time steps. Non-linearities in loading are therefore also incorporated into the analysis. Because the time-domain method allows for various non-linearities to be taken into account, it is often the preferred method for dynamic response analysis. The major drawback however is the excessive computational time and cost required for performing full time domain simulations. Due to developments in computational power this drawback has reduced significantly in the last decades.

Mainly because of its ability to accurately capture the non-linearities in the dynamic response of the system under consideration, the time-domain analysis method will be used in this thesis to assess the dynamic response of Jack-Up rigs.



**Figure 5-2:** Long term probability distribution of peak force, member diameter 1.0m



**Figure 5-3:** Long term probability distribution of peak force, member diameter 2.0m

# 5-3 Time Domain Finite Element Analysis

Like most physical systems, offshore structures like Jack-Ups can be modelled using a finite number of nodes and elements. Each node has 6 degrees of freedom (x, y, z, rx, ry, rz). The total number of degrees of freedom N is therefore given by  $6 \times no.$  of nodes. Nodes are connected by elements. Different element types exist but simple 2-node beam elements suffice in accurately modelling the structural characteristics of a Jack-Up.

For classical mechanics, this system of nodes and elements can be described in terms of motion and time using the equation of motion:

$$[M][\ddot{U}] + C[\dot{U}] + K[U] = F(t)$$
(5-1)

[U] is the DOF vector which holds N degrees of freedom. For 3D models, N is given by 6 x nr. of nodes used to describe the geometry of the system. The remaining structural information regarding mass, damping and stiffness is captured in matrices M, C, K respectively. Lastly matrix F describes the external forcing applied to the system. Equation (5-1) therefore describes a system of N differential equations which is solved for time steps  $\Delta t$  which can be used to extract displacements and reaction forces at different nodes.



**Figure 5-4:** Force spectrum for a drag-dominated member showing forcing harmonic at 3f

**Modal Analysis** Instead of solving the differential equations described in (5-1) for time steps to obtain insight into the way a structure vibrates, modal analysis allows a quick and efficient way of gaining insight into the dynamic properties of a system. In modal analysis the vibration of the structure is considered to be a superposition of the normal modes of the system. For undamped systems the vibration modes and frequencies are found by solving the eigenvalue problem given by:

$$(K - \lambda M) = 0 \tag{5-2}$$

Modal analysis will be used in Chapter 6 to identify natural periods of the model in various configurations.

#### 5-3-1 Mass Matrix - M

Structural elements have distributed mass which is characterized by the density of their material. Upon translation or rotation of the associated nodes these result in inertia forces which are included in the EoM. This results in an  $N \times N$  mass matrix which describes how these masses are distributed in the structural model.

There are two sources of mass which have to be taken into account in the dynamic response analysis of Jack-Ups:

• Structural Mass comes from the density of the materials used in the construction of the rig. Approximately 70 % of this mass is situated at the hull, whilst the remaining

30% is located at the Jack-Up legs. The mass at hull level is modelled using a number of lumped masses spread around the CoG of the hull. The mass associated with the legs is modelled simply by stating density of the leg element material.

• Added Mass As the Jack-Up is excited by incoming waves the submerged parts of the legs move through the water. This means part of the water surrounding the truss legs is also set in motion which will result in inertia forces in the system. These inertia forces are captured in the EoM by using the added mass principle. Mass is added to the submerged legs to model this behaviour. In elevated conditions the nodes forming the Jack-Up legs will mainly move in the x-y plane and show very little movement in z-direction. For this reason only the added mass in x and y directions need to be specified.

#### 5-3-2 Damping Matrix - C

Jack-Ups dissipate energy as they are excited by incoming waves. This energy dissipation is included in the equation of motion in the  $[C][\dot{U}]$  term. Damping in Jack-Ups comes from various sources. The magnitude of damping from these sources is often expressed as a percentage of the critical damping  $\zeta_c$ . Critical damping occurs when a system converges to zero as fast as possible without oscillating.

#### **Rayleigh Damping**

When solving the eigenvalue problem given by (5-2) the damping term is omitted to give a mathematically solvable problem. The inclusion of damping significantly increases the difficulty of solving a set of coupled dynamic equations.

For this reason Lord Rayleigh [1877] proposed a damping matrix C which is linearly proportional to the mass and stiffness matrix of a system:

$$C = \alpha M + \beta K \tag{5-3}$$

This formulation of the damping matrix is also known as 'Rayleigh damping', or 'classical damping'. It significantly reduces the complexity of performing time domain runs of the system.

Rayleigh damping is widely used throughout the industry but care must be taken in its application. The major downside of Rayleigh damping is that the resulting damping ratios vary as response frequency varies. This can cause over-damping of very low or very high vibration modes [Clough and Penzien, 1975].

To determine the constants  $\alpha$  and  $\beta$  the desired percentage of critical damping  $\zeta_c$  at two frequencies ( $\omega_1$  and  $\omega_2$  in Hz) is used as a starting point. The Rayleigh constants are then found by solving the following system of equations:

$$\zeta_{1,2} = \frac{\alpha}{2\omega_{1,2}} + \frac{\beta\omega_{1,2}}{2}$$
(5-4)

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The resulting damping function is displayed in Figure 5-5 which clearly shows the issue of underestimation of damping between the specified frequencies and (more importantly) a significant overestimation of damping at higher or lower frequencies.



**Figure 5-5:** Total rayleigh damping for different frequencies  $\omega$ . Total damping curve and therefore  $\alpha$  and  $\beta$  are determined by the amount of damping and location of the points  $\omega_1$  and  $\omega_2$ .

# 5-3-3 Stiffness Matrix - K

The stiffness of a system is defined as the resistance offered to deformation. In Jack-Ups stiffness originates from a number of sources of which the dominant stiffness is the structural stiffness which comes from the steel structure that comprises the Jack-Up. The elastic (and plastic) properties of the steel used create resistance to deformation and are given in the  $N \times N$  stiffness matrix K. Another major stiffness source is the foundation that is created between the Jack-Up legs and the underlying soil by the spudcans.

# 5-4 Modelling of a Jack-Up

Jack-Ups are often only excited in their first vibration modes. This is mainly due to the relatively high point of action of the oscillating wave forces. Therefore, a simple model of the structure can be sufficient to accurately model the dynamic response. Detailed models require more time to build and might introduce additional (higher) modes that are not excited in real-life which might result in false results from the computer analysis. To capture the dynamic response of a Jack-Up, the following aspects have to be modelled:

#### 5-4-1 Modelling of Leg

The leg design influences the M, C, K and F matrices and therefore forms an important part of the model. As described in Chapter 4, a detailed leg model leads to excessive computational requirements. The structural and hydrodynamic characteristics can be imitated using an equivalent pipe model as well. The following properties need to be matched between the two models:

# Stiffness: $EI = E \cdot \frac{\pi}{64} \left( D_o^4 - D_i^4 \right)$

The lateral bending stiffness of the Jack-Ups legs dominates the stiffness of the structure in surge/sway direction. It is proportional to the modulus of elasticity E and the moment of inertia of the leg cross section I. The product of the two should match the stiffness of the detailed leg model. The moments of inertia for the cross sections of the detailed and simplified leg models are given in Figure 5-6 and Figure 5-7.



Figure 5-6: Detailed leg cross section and moment of inertia



Figure 5-7: Equivalent leg cross section and moment of inertia

# Weight per meter: $F_w = \rho g \frac{\pi}{4} \left( D_o^2 - D_i^2 \right)$

The weight per meter vertical leg section for the equivalent leg model is easy to find and depends on the area of the cross section and the density used for its material. The latter can be tuned to give the correct mass (and therefore weight) for different values of  $D_o$  and  $D_i$ .

#### Buoyancy per meter: $F_B = \rho_s g \frac{\pi}{4} D_o^2$

The buoyancy of the equivalent model will be significantly higher than that of the detailed model. This can introduce errors into the model as it will artificially reduce the weight of the submerged leg section. The USFOS program allows an alternative buoyancy diameter which overrides the actual diameters of the submerged elements. In this way the buoyancy can be altered to match the equivalent leg model to the detailed leg model.

#### **Drag Loads:** $D_e C_{D_e} = D_o C_{D_{e,model}}$

The  $D_e C_{D_e}$  product is used in Morison's equation to calculate hydrodynamic drag loads and therefore needs to match that of the equivalent model. Since  $D_o$  will be significantly higher than  $D_e$  the  $C_D$  value can be tuned in the model to match the hydrodynamic drag properties of both models.

# Inertia Loads: $A_e C_{A_e} = \frac{\pi}{4} D_o^2 C_{A_{e,model}}$

Similar to the drag term, the inertia term also needs to be matched. This can be one by tuning  $C_A$  of the equivalent model to achieve the correct magnitude of the  $A_e C_{A_e}$  term.

#### Added Mass:

Lastly, the added mass of the equivalent leg model needs to match that of the detailed model. USFOS allows separate values for added mass to be stated in the model file which overrides any calculated added masses.

#### Benchmark

A benchmark was performed to validate the stiffness properties given in Figure 5-6 and Figure 5-7. A FEM model of a F&G JU2000E leg was used in order to verify the values obtained through calculation. A unit force is applied in both horizontal and axial direction on a modelled leg which is clamped at the bottom. The procedure is displayed in Figure 5-8 and Figure 5-9:

The results of the benchmark are shown in Table 5-1:

Property	Calculations	FEM Results	Diff. [%]
$A [m^2]$	0.52	0.52	0%
$I [m^4]$	15.14	14.92	-2%
$A_{\rm shear} \ [m^2]$	0.05	0.05	-3%
$J [m^4]$	1.50	1.53	+2%

Table 5-1: Comparison between calculated and FEM analysis leg structural properties

For both methods the moment of inertia and axial cross sectional area are in satisfactory agreement. The calculated moment of inertia is slightly higher when compared to the results from the FEM analysis. This difference can be explained by the fact that the bracing is neglected in the calculation procedure for stiffness given in the SNAME Guidelines.



**Figure 5-8:** Shear test on detailed FEM model of leg in order to determine equivalent structural properties for modelling

**Figure 5-9:** Axial compression test on detailed FEM model of leg in order to determine equivalent structural properties

# 5-4-2 Modelling of the Hull

In the FEM model, the hull serves the following purposes:

- To connect the three legs at the height of the rack chocks
- Allow the hull weight and variable deck loads to be applied

The above objectives can be reached by using a very limited number of nodes which are connected by weightless rigid elements which from the deck. The sum of the hull mass and variable deck mass is then distributed over these nodes to from weight after application of gravitational acceleration in the program. Although the hull itself will introduce flexibility into the structure, its stiffness is so much greater than that of the relatively long and slender legs that the use of rigid elements gives a satisfactory representation.

# 5-4-3 Modelling the Leg-Hull Connection

The flexibility of the leg-hull connection also contributes to the total stiffness of the system and is therefore considered in the dynamic response analysis. Its influence has however decreased drastically with the introduction of rack chocks in the new breed of Jack-Up designs. Rack chocks are designed to form a very stiff connection between the hull and the chords and therefore no longer play a dominant roll in the dynamic response analysis (impact on natural period < 1%)<sup>1</sup><sup>2</sup>. For this reason the leg-hull connection is modelled as a rigid connection.

# 5-4-4 Modelling the Spudcan

The model of the Jack-Up foundation plays an important role in the dynamic response of the system. The following spudcan models can be used in the model:

- **Pinned Foundation:** When using pinned foundation the connection between the spudcan and the foundation underneath is allowed to rotate freely. The foundation is constrained from moving in x, y and z direction.
- **Fixed Foundation:** The opposite of a pinned foundation is the fixed foundation. The nodes at the spudcan-soil interface are restricted in all six degrees of freedom.
- Clay/Sand SPUD Foundation: The USFOS software has an incorporated element which can be used to model the behaviour of a spudcan-soil interface for both sands and clays. The model was developed in-house at Shell to be implemented into time domain software [van Langen, 1993]. The stiffness of the foundation element K for displacement increments u and force increments F is related as follows:

$$\dot{Q} = K\dot{u} \tag{5-5}$$

Of which the matrices are given as follows:

$$K_t = \begin{bmatrix} k_h^e & 0 & 0\\ 0 & k_v^e & 0\\ -\frac{k_\theta^e k_v^e}{d} \frac{\partial f}{\partial V} & -\frac{k_\theta^e k_h^e}{d} \frac{\partial f}{\partial H} & (k_\theta^e - \frac{k_\theta^e k_\theta^e}{d} \frac{\partial f}{\partial M}) \end{bmatrix}; Q = \begin{bmatrix} \dot{H} \\ \dot{V} \\ \dot{M} \end{bmatrix}; \dot{u} = \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{\theta} \end{bmatrix}$$
(5-6)

The values for the elastic stiffnesses  $k_h$ ,  $k_v$  and  $k_{\theta}$  are found using:

$$K_V = \frac{2G_V D_{eff}}{(1-v)}; \quad K_H = \frac{16G_H D_{eff}}{(1-v)(7-8v)}; \quad K_\theta = \frac{G_R D_{eff}^3}{3(1-v)}$$
(5-7)

#### 5-4-5 Modelling of Damping

There are a number of energy dissipation mechanisms which add up to form the damping of the system. Each contribution is given in terms of a percentage of the critical damping  $\zeta_{crit}$ .

- Structural Damping 2%: Occurs in all structures. It is caused by energy dissipating due to yielding of member material (hysteric damping) and energy dissipation due to energy losses in joints (frictional damping).
- Soil Damping 2%: Is caused by hysteric energy dissipating in the soil surrounding the spudcan foundation.

<sup>&</sup>lt;sup>1</sup>http://www.hse.gov.uk/research/rrpdf/rr037.pdf

<sup>&</sup>lt;sup>2</sup>http://www.hse.gov.uk/research/otopdf/2001/oto01036.pdf

• Hydrodynamic Damping 3% (or 0%) Dynamic loads cause the Jack-Up legs to move back and forth through the surrounding water and air. This movement causes viscus damping to occur between the leg members and the surrounding fluid. This damping has a magnitude of approximately 3% of  $\zeta_{crit}$  but is often incorporated into the analysis by instructing the software to incorporate relative velocities into the analysis. The velocity profile due to wave and current is now calculated relative to the movement of elements. In this way the hydrodynamic damping is automatically incorporated into the analysis.

# 5-5 Analysis Set-Up

An IT structure was set up that allows efficient simulating to be done in order to gain insight into the various parameters that influence the dynamic response of a Jack-Up. The IT structure uses UNIX, an operating system, to perform batch runs in USFOS. This OS was chosen because USFOS is a UNIX based program. The user specifies a head.fem and a model.fem file which describe the USFOS analysis. An additional parameters.txt file is added which contains the variables that need to be varied in the head.fem or model.fem file for the batch run. A UNIX script which is executed in Cygwin creates the folder structure and performs the batch runs. USFOS plugin Dynmax is also executed to extract max BSH and OTM values from the simulation time trace. These are then extracted and processed using MATLAB to form the DAF spectrum of the model. The IT structure is shown in Figure 5-10:



Figure 5-10: IT Flow Diagram

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# 5-6 Input Parameters

Analysis of modern Jack-Up rigs allows 'general' models to be made. These have structural properties similar to the rigs that have been identified in Chapter 3 representing the modern Jack-Up designs. Two models were made, Model A and Model B, which represent the relatively smaller modern designs (KFELS B Class, F&G JU2000E) and the relatively big modern designs (CJ-62, CJ-70, KFELS N-Class) respectively. Table 5-2 summarizes the structural properties of the two models which will be used to determine the dynamic response characteristics of modern Jack-Up designs.

Property	Model A	Model B	
Leg Spacing (Transv.)	50	65	[m]
Bay Height	10	10	[m]
Nr. of Bays	16	19	[-]
Hull Weight	14000	18000	[tons]
Unit Leg Weight	10	11	[tons/m]
Unit Leg buoyancy	1.5	1.7	[tons/m]
Chord Spacing	12	16	[m]
Height of Fixation above CoG	2	2	[m]
Spudcan Diameter	18	22	[m]

Table 5-2: Dynamic analysis input parameters, model A and B

All the information in the preceding sections has been incorporated into an excel file which automatically generates the model.fem file which can be used in USFOS. An example of such a file is found in Appendix B.

# 6

# **Dynamics - Results**

The selected methodology for dynamic response analysis of Jack-Ups was described in the previous chapter. Chapter 6 presents the results of dynamic response analysis for models A and B in different water depths and spudcan boundary conditions. The results of the dynamic response analysis are split into three parts, namely: natural periods, DAFs for regular waves and DAFs for irregular waves.

# 6-1 Natural Periods

Determination of the natural periods is a fundamental starting point in dynamic response analysis. The first modes are most likely to be excited. They consist of a surge, sway and torsional mode as displayed in Figure 6-1:



**Figure 6-1:** Jack-Up typical top view illustrating first vibration modes, from left to right: sway, surge and rotational.

# 6-1-1 Analytic Estimation of Natural Periods

The natural periods of Jack-Ups can be approximated using SDOF equivalent systems. They can provide values which can be used to verify the natural periods calculated by eigenvalue FEM analysis. The estimation is based on a system described by:

- An equivalent mass  $M_e$  representing a combination of the hull mass and a contribution of the mass of the Jack-Up legs.
- An equivalent spring  $K_e$  representing the stiffness of the legs and various other contributions. The latter consists of a stiffness contribution due to the spudcan-soil interface, the leg to hull connection and p $\Delta$  effect.

The natural period is then given by the following (well-known) solution of a SDOF mass-spring system:

$$T_n = 2\pi \sqrt{\frac{M_e}{K_e}} \tag{6-1}$$

Where all Jack-Up particular information has been stored in  $M_e$  and  $K_e$ .

#### Equivalent Mass $M_e$

The equivalent mass is given by:

$$M_e = \frac{M_{hull}}{N_{legs}} + \frac{M_{leg}}{2}$$

For a modern Jack-Up the hull weights are approximately 15,000 tons and the legs unit weight is approximately 10 tons/meter. With these values and assuming a water depth of 100m the equivalent mass value is roughly 5,500 tons.

#### Equivalent Stiffness K<sub>e</sub>

Neglecting the stiffness of the leg to hull connection and assuming total fixity at the spudcansoil interface, the equivalent stiffness can be approximated by the leg stiffness modified by a  $p\Delta$  factor:

$$K_e = \frac{3EI}{L^3} \cdot \left[1 - \frac{P}{P_e}\right]$$

The moments of inertia of Jack-Up legs are mainly determined by the chord cross-sectional area and the chords spacing which gives values of approximately 15  $m^4$  for modern leg designs. Assuming a water depth of 100m this gives equivalent stiffness values of approximately 10  $MNm^{-1}$ 

With these estimates for the equivalent mass and stiffness the natural period of the surge and sway mode of a modern Jack-Up operating in 100 meter water depth is estimated:

$$T_n \approx 5s \tag{6-2}$$

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#### 6-1-2 Natural Periods from Modal Analysis

FEM software allows for quick calculation of the natural periods of a system. The program performs a modal analysis and calculates the eigen-frequencies of the system. The natural periods of models A and B were calculated for different water depths and spudcan boundary conditions. The results are given in the following table:

	Model A				Model B			
WD [m]	$\mathbf{F}$	$\mathbf{S}$	$\mathbf{C}$	Р	$\mathbf{F}$	$\mathbf{S}$	$\mathbf{C}$	Р
90	3.6	5.6	6.4	7.2	3.3	5.2	6.0	6.6
100	4	6.2	7.1	8.4	3.7	5.8	6.7	7.6
110	4.5	6.8	7.8	9.6	4.1	6.4	7.4	8.6
120	5	7.5	8.6	11	4.6	7	8.1	10
130	5.5	8.1	9.3	12.6	5	7.8	9.0	11.2
140	6.1	8.8	10.1	14.2	5.6	8.4	9.7	12.6
150	-	-	-	-	6.1	9.1	10.5	14.2

Table 6-1: Natural periods [s] for varying parameters

#### 6-1-3 Natural Periods for Modern rigs

Moving into deeper water means extending the leg length below the hull. This raises the COG of the structure relative to the sea-floor. The natural period increases due to this increase in leg length. This is partially counteracted by the increased leg stiffness that is required for deeper water depths.

# 6-2 Dynamic Amplification Factor - Regular Waves

#### 6-2-1 Regular Waves and Varying Period

The Dynamic Amplification Factor (DAF) is defined as the ratio of the dynamic to the quasistatic response of a system:

$$DAF = \frac{x_{dyn}}{x_{stat}} \tag{6-3}$$

Calculating DAFs for different incoming wave periods allows a spectrum to be created which gives insight into the dynamic response characteristics of a system. To obtain a DAF spectrum, the model was run both quasi-statically and dynamically while varying the period of the regular wave input. The ratio of the extreme BSH to the extreme OTM in both runs gives the corresponding DAFs:

$$DAF_{BSH/OTM} = \frac{BSH/OTM_{max,dyn}}{BSH/OTM_{max,stat}}$$
(6-4)

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The resulting DAF spectrum for model A in 120m water depth and pinned condition (A120P) is shown in Figure 6-2:



Figure 6-2: DAF spectrum for regular wave input for A120P model.

The following can be observed:

- For  $T_w \ll T_n$  the DAF drops below 1 and the response of the structure is bigger for the quasi-static run when compared to the full dynamic run. The system is inertiadominated. The excitation period is too low for the system to be dynamically excited.
- For  $T_w \approx T_n$  the DAF shows a peak which indicates occurrence of resonance. The excitation period of the incoming waves is similar to that of the structure's natural period  $T_n$ . The maximum amplitude of the DAF is determined by the amount of energy-dissipation (damping) in the system.
- For  $T_w >> T_n$  the DAF tends to approach unity value. This indicates both fully dynamic and quasi-static run give similar values for BSH and OTM. The response has become stiffness dominated. The wave periods are too high for the structure to be dynamically excited, it responds in a quasi-static way for both runs.

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The DAF spectrum for model A in 100 m of water depth and pinned condition (A100P) is shown in Figure 6-3:



Figure 6-3: DAF spectrum for regular wave input for A100P model.

The spectrum shows a resonance peak at  $T_n = 8.4s$  but also shows a (smaller) peak at  $T_w = 16.8s$ , or  $T_w = 2T_n$ . Sub-harmonic peaks were observed for all model configurations when the excitation period was an integer multiple of the natural period of the system ( $T_w = 2T_n, 3T_n...$ )

The sub-harmonic peaks actually originate from superharmonics in the wave loading and are caused by the following non-linearities in the wave loading:

- Drag Loading: As shown in Figure 5-4, the drag term in the wave loading introduces harmonics onto the forcing. Without current, these only occur at odd fractions of the excitation period  $(T_w/3, T_w/5, ...)$  and will therefore not show resonance peaks at  $T_w = 2T_n$ .
- Stretching: Calculating the wave kinematics involves stretching the velocity and acceleration profile to the instantaneous water surface instead of the mean sea level. This introduces higher order terms in the wave loading which potentially excite the structure at its natural period. For stretching effects the superharmonics occur at both even and odd fractions of the excitation period  $(T_w/2, T_w/3, ...)$

These non-linearities emphasize the importance of performing time-domain simulation as they are hard to capture in a linearised analysis.

#### 6-2-2 Regular Waves and Varying Wave Height

For linear systems, the DAF is only a function of excitation. For non-linear systems the magnitude of excitation also plays a role in the magnitude of the DAF. To demonstrate this feature the A120P model was run for constant frequency but varying magnitude. The results are given below (Figure 6-4):



**Figure 6-4:** DAFs for different wave heights for the A120P model. OTM DAF increases with wave height while the opposite is found for BSH DAF. The period of incoming waves was kept constant at T = 11s which corresponds to the natural period of the model.

The trends shown in Figure 6-4 indicate the presence of non-linearities in the model. As the magnitude of vibration increases the p-delta effect causes a change in natural period. Therefore the BSH and OTM DAFs vary for different wave heights.

#### 6-2-3 Regular Waves and Varying Heading

The first vibrational modes of a typical Jack-Up were identified in Section 6-1. These are readily excited by multiples of 60 degree headings. Combinations of vibration modes can also occur when the weather comes from an angle different than the ones describe above. This effect was studied in the runs below. The A100F model was chosen and run for different headings at a wave period that coincides with the model's natural period for surge and sway. The results are given in Figure 6-5.



**Figure 6-5:** DAFs for different headings for the A100F model, clearly illustrating relatively large dynamic amplification for directions that are in line with vibration modes (0, 60, 120, 180, 240 and 300°).

The DAF is largest when the wave heading coincides with a sway direction of the model. The sequence of leg loading is also determining in the amplitude of the DAF value for these cases. The 60, 180 and 300 degree headings show highest DAF, where two legs are excited first, after which the third leg is excited later. Headings 0, 120, and 240 give a reduced DAF, where first a single leg is excited, and the two remaining legs are excited simultaneously at a phase difference which is related to the leg spacing and wave propagation velocity. Because the DAF is largest for the 60, 180 and 300° heading, this direction will be used to study DAFs throughout the remainder of the thesis.

# 6-3 Dynamic Amplification Factor - Irregular Waves

Ocean sea states are irregular by nature. They can be modelled by superposition of linear waves of different phase, frequency and amplitude. For limited fetch the wave characteristics of an irregular sea-state are captured in a JONSWAP spectrum which can be inserted directly into USFOS. The quantity to be calculated from the irregular run is the Most Probable Extreme Maximum DAF,  $DAF_{MPME}$ , which is used to model the inertial load set applied to the 50-year return wave which the structure has to be able to withstand. Determining the MPME of a non-Gaussian process is not trivial however and requires the following approach.

#### **Determining Most Probable Maximum Extreme**

The MPME value is decisive in the final DAF result and has been a subject of much debate since the publishing of the SNAME Guidelines in the beginning of the 90's. Throughout the years several companies performed comparative studies into the different statistical methods available to calculate the MPME given the statistical properties of a number of time domain runs. The preferred method is one proposed by Winterstein in 1988 which was further refined by Jensen in 1991.

The Winterstein Jensen method consists of fitting a Hermite polynomial of Gaussian processes to transform the non-linear, non-Gaussian process in question (BSH, OTM) into a mathematically tractable probability density function. This is achieved using the following steps:

- 1. Calculate the  $\mu$  (mean),  $\sigma$  (std. deviation),  $\alpha_3$  (skewness) and  $\alpha_4$  (kurtosis) of the parameter in question.
- 2. Calculate the following quantities from the parameters found in step 1:

$$h_3 = \alpha_3 / \left( 4 + 2\sqrt{1 + 1.5(\alpha_4 - 3)} \right)$$
  

$$h_4 = \left[ \sqrt{1 + 1.5(\alpha_4 - 3)} - 1 \right] / 18$$
  

$$K = \left[ 1 + 2h_3^2 + 6h_4^2 \right]^{-\frac{1}{2}}$$

3. It is necessary to achieve a more accurate result by determining teh solution of the following equation for  $C_1$ ,  $C_2$  and  $C_3$ :

$$\begin{split} \sigma^2 &= C_1^2 + 6C_1C_3 + 2C_2^2 + 15C_3^2 \\ \sigma^3 \alpha_3 &= C_2(6C_1^2 + 8C_2^2 + 72C_1C_3 + 270C_3^2) \\ \sigma^4 \alpha_4 &= 60C_2^4 + 3C_1^4 + 10395C_3^4 + 60C_1^2 + 4500C_2^2C_3^2 + 630C_1^2C_3^2 + 936C_1C_2^2C_3 + 3780C_1C_3^3 + 60C_1^3C_3 \end{split}$$

Using the following initial guesses:

$$C_1 = \sigma K(1 - 3h_4)$$
$$C_2 = \sigma Kh_3$$
$$C_3 = \sigma Kh_4$$

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The final values for K,  $h_3$  and  $h_4$  are the found using:

$$K = (C_1 + 3C_3)/\sigma$$
$$h_3 = C_2/(\sigma K)$$
$$h_4 = C_3/(\sigma K)$$

4. The most probable value, U, of the transformed process is computed by using the following equation:

$$U = \sqrt{2ln(N \times \frac{3hours}{t_{simulation}})}$$
(6-5)

Where U is a Gaussian process of zero mean, unit variance

5. The most probable maximum, transformed back to the standardised variable, z, is then given by:

$$z_{MPM} = K[U + h_3(U^2 - 1) + h_4(U^3 - 3U)]$$
(6-6)

6. The MPME for the process under consideration is now given:

$$R_{MPME} = \mu + \sigma z_M P M \tag{6-7}$$

The Dynamic Amplification Factor is finally found by division of the MPME for a quasi-static run and a dynamic run:

$$DAF_{BSH/OTM} = \frac{MPME_{BSH/OTM,dyn}}{MPME_{BSH/OTM,stat}}$$
(6-8)

#### 6-3-1 DAFs for increasing Water Depth

Irregular wave runs were performed for models A and B in water depths ranging from 90 to 150 m. These runs were performed for both fixed and pinned boundary conditions. Figure 6-6 and Figure 6-7 show the results for model A, Figure 6-8 and Figure 6-9 show the results for model B.



**Figure 6-6:** DAF for increasing WD, model A, pinned foundation



Figure 6-7: DAF for increasing WD, model A, fixed foundation



**Figure 6-8:** DAF for increasing WD, model B, pinned foundation

Figure 6-9: DAF for increasing WD, model B, fixed foundation

Models A and B show very similar results in terms of DAFs for increasing water depth. This is to be expected since the increase in hull mass of model B is accompanied by an increase in leg stiffness. The natural periods of both models are therefore very similar at given water depths. The DAFs increase significantly with each depth increase for the pinned models. This is due to the fact that the natural periods of the first modes increase and approach the excitation period of the irregular sea-state ( $T_{wave}/T_n \approx 1.0$ ). This effect is less profound for the fixed models. The reason for this is that although the natural periods increase, they are still well away from the excitation periods of the seastate ( $T_{wave}/T_n \ll 1.0$ )
#### **6-3-2** DAFs in terms of $T_p/T_n$

The results from the previous page can be combined with the natural periods obtained earlier to relate the DAFs of the different model configurations to the ratio of the significant wave period to the structure's natural period. Results are given in the plot below (Figure 6-10):



**Figure 6-10:** DAFs as a function of  $T_p/T_n$ . DAFs increase for values of  $T_p/T_n \sim 1$  and decrease for  $T_p/T_n >> 1$ .

The results show similar results to those seen for regular wave analysis in Figure 6-2. As the wave period increases (and the ratio  $T_p/T_n$  increases) the DAFs tend to decrease towards unity value. When the excitation periods match those of the system's natural period the DAFs increase. Although the DAFs will vary according to significant wave height  $H_s$  as well, the above results suggest the DAFs to be expected for a Jack-Up in irregular sea-states can be estimated based on the ratio of the significant wave period to the natural period.

#### **6-3-3 DAF** for different $H_s$

The significant wave height  $H_s$  was kept constant for the runs described previously. To gain insight into the behaviour of the DAFs for both BSH and OTM,  $H_s$  was varied while all other parameters kept constant for the following runs. The results are given in Figure 6-11:



**Figure 6-11:** DAFs for the A120P model where  $H_s$  was varied between 6-16m with 1m intervals. All other parameters were kept constant in the analysis

Similar to the results in Figure 6-4 we expect DAFs to vary because of the non-linear nature of the system. The trend is however less consistent when compared to the results of a regular wave test which might be accredited to the (random) irregular nature of the wave- and therefore loading-spectrum. A decreasing DAF for BSH is however observed, similar to the results found for regular waves.

#### 6-3-4 Consistency of runs

USFOS generates the irregular sea-state according to the seed number specified by the user. Different seeds result in different sea-states which will also affect the magnitude of the calculated DAFs. For this reason SNAME recommends multiple 3-hour storm simulations (and Shell extends this to multiple 10-hour storm simulations). Table 6-2 shows the results of 7 sea-state approved runs (out of a total of 10 runs) for the A120P model:

**Table 6-2:** Consistency of DAFs for different seeds. Additional seas-state check is performed. Significant variation is present in the results. Sea-states 2,3 and 8 were not approved according to the criteria stated in the Guidelines.

		D	AF
Seed Nr.	Sea-state Approved	BSH	OTM
1	YES	1.82	2.38
2	NO	2.02	2.76
3	NO	1.84	2.40
4	YES	1.97	2.52
5	YES	1.93	2.65
6	YES	2.11	2.58
7	YES	2.03	2.99
8	NO	2.01	2.57
9	YES	2.15	2.80
10	YES	2.29	3.28

The results for BSH have a mean of 2.04 and a standard deviation of 0.15 so a relative standard deviation of 7.4%. This compares to the OTM mean of 2.74 and standard deviation 0.31 which gives an RSD of 11.3%. We see there is significant variation between results which is also the reason why SNAME stipulates use of multiple 3-hours runs to obtain an averaged DAF for both BSH and OTM.

# Limits

Chapter 4 to 7 demonstrated the effect of moving to deeper waters in terms of environmental loads, resistance and dynamic response. Modern designs were justified in terms of their increased leg spacing, spudcan radii and leg stiffness. The design philosophy of using three truss legs on a triangular hull has remained reasonably consistent throughout the last five to six decades whilst the water depth and environmental capabilities have increased up to 550' ( $\sim$ 170m) in harsh environments for the most recent rig designs. Identifying the limits in this design philosophy allows oil companies like Shell to shape the future of offshore developments.

#### Methodology

In order to determine the limits of current Jack-Up design philosophy, two preliminary models will be developed in the following section. They are designed for 200 and 250 meters of water depth respectively. The following design flowchart is used:



Figure 7-1: Jack-Up design process

#### 7-1 Dynamic Response

The dynamic response properties of the designs is used as a starting point. The first vibration modes of Jack-Ups are dominated by the weight (and CoG) of the hull and the bending stiffness of legs. In 2013 a study was completed by [Kaiser et al., 2013] at the Louisiana State University describing a model which predicts Jack-Up weights and displacements. The result was a relationship between water depth (in feet) and Jack-Up weights given by the following expression:

$$Displacement = 0.1119 * WD^2 - 224.15$$
(7-1)

Displacement and therefore mass were found to vary quadratically with water depth:

$$m \propto W D^2$$
 (7-2)

Eq. (7-1) estimates the lightship displacement of a 200m design at 48000 tons and the lightship displacement of a 250m design at 75000 tons. 30% of these displacement are assumed to account for the weight of the legs whilst the remainder is attributed to the hull and its variable loads.

These values can be used to determine the required stiffness of the truss legs. To prevent excessive resonance the natural period for first vibration modes should not exceed 10s. Natural periods can be approximated using SDOF analogy (as described in Chapter 5) which gives the following relationship between mass, stiffness and natural period:

$$T_n = 2\pi \sqrt{\frac{m}{k}} \tag{7-3}$$

Therefore an increase in mass should be directly proportional to an increase in stiffness:

$$m \propto k$$
 (7-4)

or

$$k \propto W D^2 \tag{7-5}$$

The stiffness of a Jack-Up in surge and sway direction for the first vibration modes can be estimated using the bending stiffness of a cantilever beam, hence:

$$k \propto \frac{EI}{L^3} \tag{7-6}$$

Where  $L \sim WD$  and E can be assumed constant. Combining Eq. (7-5) and Eq. (7-6) gives:

$$I \propto W D^5 \tag{7-7}$$

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The moment of inertia for a triangular truss leg is dominated by the (cross sectional) chord area  $A_c$  and the chord-to-chord spacing h and can be estimated by the following equation (as described in Chapter 5):

$$I = 0.5h^2 A_c \tag{7-8}$$

This finally relates an increase in water depth to the required increase in chord-to-chord spacing and chord area:

$$WD^5 \propto h^2 A_c \tag{7-9}$$

Using these relationships the following table can be generated to give the (dynamic) design characteristics of a 200 and 250m Jack-Up:

	150m	200m (+33%)	250m (+66%)
m <sub>total</sub> [tons]	27000	48000 (+78%)	75000 (+177%)
$m_{hull}$ [tons]	18900	$33600\ (+78\%)$	52500 (+177%)
I $[m^4]$	30	126 (+321%)	386 (+1186%)
$A_c \ [m^2]$	0.25	0.30	0.35
Chord Spacing [m]	15.5	29	47

Table 7-1: Dynamic properties of designs for 200m and 250m Jack-Up

A 33% increase in water depth (from 150m (current limits) to 200m) requires an increase in leg stiffness of 321%. If the chord area increases by 30% as well this means the chord-to-chord spacing is required to increase by 80%.

#### 7-2 Environmental Loads

#### Hydrodynamic Loads

Water depth and chord spacing dictate leg design and therefore allow for estimation of the hydrodynamic loads. Using split-X bracing the following hydrodynamic properties have been estimated using the method which was also used in Chapter 4 and of which an example is found in Appendix A. The following leg properties are estimated:

16

5.35

29

7.4

47

11.1

Chord Spacing

 $D_e * C_D$ 

Table 7-2: Hydrodynamic properties of designs for 200m and 250m Jack-Up

The resulting hydrodynamic loads can be calculated using equivalent leg models with matching hydrodynamic properties.

#### Wind Loads

To evaluate the wind loads of the fictional 200 and 250m Jack-Up designs the wind areas of the two designs need to be estimated. A reasonable assumption is that the wind areas increase proportionally with water depth (as the rigs gets bigger in order to provide stability to the increasing leg lengths). The wind area of the 200 and 250m designs are therefore estimated at  $7500m^2$  and  $9400m^2$  respectively.

#### **Total Environmental Loads**

The environmental loads can now be estimated and used to determine the required leg spacing:

**Table 7-3:** Typical environmental loads and required leg spacing for 150, 200 and 250m Jack-Up. Environmental loads were calculated for  $H_{max} = 25m$ ,  $T_{ass} = 15s$  and  $v_{wind} = 40m/s$ 

WD [m]	1	50	2	00	250				
	BSH	OTM	BSH	OTM	BSH	OTM			
Wave	6.7	895	8.5	1555	12.1	2817			
Wind	7.3	1307	9.7	2236	12.2	3411			
Total	13.9	2201	18.2	3791	24.3	6228			
Leg Spacing [m]	42	1.1	3	9.8	41.9				

Due to the exponential relationship between water depth and hull mass, the leg spacing does not need to increase. The increased OTM resistance due to the increased mass is sufficient to supply the required OTM resistance for the design. Increased leg spacing will however also result in lower bearing pressures and allows from smaller spudcans to be used.

#### 7-3 Limits

The preceding section shows that moving to deeper waters requires a rapid increase in leg stiffness. Environmental loads also increase but these can be counteracted by increasing leg spacing, generating higher OTM resistance and also lowering the maximum bearing capacity required. The stiffness is generated by increasing the moment of inertia. The latter is required to increase with  $WD^5$  in order to keep the natural period below the 10s goal which was explained in the beginning of this chapter:



**Figure 7-2:** Required moment of inertia of legs as a function of water depth. Asymptotic trend shows rapid need for increasing moment of inertia as water depth approaches 200 meters.

**Figure 7-3:** Required chord spacing of legs as a function of water depth. Asymptotic trend shows rapid need for increasing chord spacing as water depth approaches 200 meters.

Figure 7-2 shows the required increase in moment of inertia gains momentum at approximately 120m water depth after which the curve flattens. This means a small increase in water depth requires a large increase in leg moment of inertia. Large increases in leg moment of inertia are bounded by the following limits however:

• Chord spacing and RPD: Increasing chord spacing leads to spacious legs which in turns increases the length of diagonal and horizontal bracing. During jacking operations the braces offer resistance to RPD which is caused by eccentric loading of the spudcan. As brace lengths increase the resistance to buckling of the members under compression decreases. This is the reason why RPD is occurring more often in modern Jack-Up designs as described in Chapter 2.

• Chord area: The chords of modern Jack-Up designs are fabricated by rolling thick plate steel (t~100mm) into two u-shaped section with a diameter in the order of 0.6m. These are welded onto a rectangular profile which holds the rack teeth which are used in the leg-hull connection:



Figure 7-4: Typical cross-section of chord

Further increasing the chord area requires even thicker steel plates to be rolled which becomes more and more challenging also because the radius of the U-shaped sections has to remain relatively small to minimize hydrodynamic loads on the chords. This limit was also identified during an interview the Jack-Up designer GustoMSC, of which a summary can be found in Appendix C.

## 8

## Solutions

Chapter 7 demonstrated that the water depth limit of current design philosophy is bound to approximately 200 meters. The reason for this limit is the requirement of rapidly increasing leg stiffness as a result of increasing hull mass and hull elevation. This chapter presents possible solutions that attempt to omit this problem, possibly enabling Jack-Ups to be used in even greater water depths.

#### **Overview of Solutions**

The profound dynamic response seen at greater water depths leads to high DAFs and therefore adds a large load to the system. This was used as a starting point to identify possible solutions in the quest to extend the use of a self elevating platform to greater water depths. A brainstorm session was held which lead to the identification of the following concepts:

- 1. Solution I Curved Legs
- 2. Solution II Connected Legs & Flexible Leg-Hull Connection
- 3. Solution III Tuned Mass Damper
- 4. Solution IV Coupled Floater

The concepts are shown on the next page (Figure 8-1).



Figure 8-1: Overview of proposed solutions

#### 8-1 Concept 1 - Curved Legs

A Jack-Up with curved legs was selected as one of the possible solutions to improve deep water (dynamic) characteristics. A search into the history of Jack-Up designs shows the first Jack-Ups built by Marathon LeTourneau included canted legs. These Jack-Ups were used in shallow water when the foundation was soft. The canted legs reduce the required bearing capacity:



Figure 8-2: Canted leg Jack-Up design used by LeTourneau in 1960's

#### 8-1-1 Dynamic Response

**Natural period** The increased lateral stiffness reduces the natural period of the structure because it increases the stiffness of the system in x-y direction. Results for the A120P model with 0, 0.1, 0.25, 0.5 and  $1^{\circ}$  angles between adjacent leg bays are given in the following table:

**Table 8-1:** Natural periods for legs with increasing bay angles and therefore leg curvature. A clear reduction in natural period is visible.

Angle $[\circ]$	$T_n$ [s]
0	10.9
0.1	10.0
0.25	9.1
0.5	7.8
1	5.9

**Regular waves** The effect of introducing curved legs to Jack-Up design has been studied using the same analysis technique that was used to determine the global dynamic response behaviour of regular Jack-Up designs in Chapter 5. The results are shown in Figure 8-3 and Figure 8-4.



**Figure 8-3:** DAFs in regular waves for A120P model and A120P -  $0.5^{\circ}$  Curved model. Reduction in DAF around wave excitation periods is evident.



Figure 8-4: DAFs in regular waves for A120P model and A120P -  $1.0^{\circ}$  Curved model. Reduction in DAF around wave excitation periods is evident.

The natural period decreases significantly for only slight leg inclination. The natural period of the A120P - C1° model is 5.8 seconds. A resonance peak shows at  $3 \times T_n$ . This super-harmonic excitation was also identified in Chapter 6 and is caused by non-linearities due to the drag loading and wave stretching.

**Irregular waves** The decrease in dynamic response to regular waves for the various concepts will obviously be present in the dynamic response to irregular waves as well. The combination of a 3-hour storm simulation and the Wintersteijn-Jensen method for derivation of the MPME's of the two DAFs was used for the two models described in the previous paragraph. The results are given in the table below:

Model	BSH	OTM
A120P	1.82	2.38
A120P - C $0.5^\circ$	1.36	1.36
A120P - C $1.0^\circ$	1.15	1.25

Table 8-2: DAFs for irregular sea states and curved legs

The benefit of the increase in stiffness (and therefore decrease in natural period) is evident from the results from Table 8-2. The DAFs for both BSH and OTM are significantly reduced and will therefore decrease the design loads due to dynamic response of the structure.

#### 8-1-2 Verdict

The nature and magnitude of environmental loads on a Jack-Up with curved legs is identical to that on a design with straight legs. The resistance of the structure will improve however due to the introduction of curved legs. This is also the reason why jackets often employ a better angle in their design:

- The footprint of the base of the structure increases. This leads to an increased OTM resistance as the distance from the support points to the horizontal CoG position of the structure has increased.
- The stiffness of the structure in the x and y plane increases due to the curvature of the legs. The base shear due to environmental loads is directed at an angle instead of perpendicular to the supporting seabed, as is the case when using straight legs.

Although the use of curved legs has benefits in terms of the global resistance of the structure, local problems arise due to the large increase in bending moment in the Jack-Up legs. This increase is caused by the fact that the loading on the spudcan is no longer in-line with the leg-hull connection. The heavy hull will induce large bending moments in the legs which will therefore require increased brace diameters. This in turn leads to higher wave loads and therefore shows the difficulties of trying to find solutions for extending the water depth limit of Jack-Ups. Possible gains in one area of the assessment lead to compromises in another.

#### 8-2 Solution 2 - Connecting Legs & Flexible Leg-Hull Connection

A different approach to improve the dynamic characteristics of Jack-Up designs is to increase the natural period of the system by introducing the flexibility into the leg-hull connection and connecting them above the hull.

#### 8-2-1 Dynamic Response

A system with flexible leg-hull connection can be represented by the following schematic representation (Figure 8-5):



Figure 8-5: Jack-Up with flexible leg-hull connection

The introduction of a flexible connection separates the Jack-Up into two coupled dynamic systems. Each system has its own natural frequency which will lead to resonance when excited:

$$\begin{bmatrix} 3m_{leg} & 0\\ 0 & m_{hull} \end{bmatrix} \begin{bmatrix} \ddot{x_1}\\ \ddot{x_2} \end{bmatrix} + \begin{bmatrix} c & 0\\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x_1}\\ \dot{x_2} \end{bmatrix} + \begin{bmatrix} k_l + k_h & -k_h\\ -k_h & k_h \end{bmatrix} \begin{bmatrix} x_1\\ x_2 \end{bmatrix} = \begin{bmatrix} F(t)\\ 0 \end{bmatrix}$$
(8-1)

Assuming c = 0 and  $x_i = \sin w_i t + \phi_i$  we get:

$$\omega_{1,2} = \frac{k_l m_{hull} + k_h m_{hull} + k_h 3 m_{leg} \pm \sqrt{(k_l m_{hull} + k_h m_{hull} + k_h 3 m_{leg})^2 - (4m_{hull} 3 m_{leg} k_h k_l)}}{2m_{hull} \cdot 3m_{leg}}$$
(8-2)

The leg-hull flexibility has been incorporated into the USFOS model using linear elastic springs. These have been tuned to move the natural frequencies of both system well away from the excitation periods of high energy waves. A stiffness of 100 kN/m was chosen. The resulting DAF values for different wave periods is given in Figure 8-6.



**Figure 8-6:** DAF spectrum comparison between rigid and flexible leg-hull connection. Clear reduction of DAF around wave periods is evident.

The introduction of flexibility in the leg to hull connection has lead to a significant reduction in dynamic response around the high energy wave periods ranging between 8 to 16 seconds. The natural period of the connected legs lies at around 7 seconds which is below the period of high energy waves. This vibration mode also causes a small super-harmonic resonance peak at T=14.5 seconds but its magnitude is very limited. The natural period of the hull vibrating between the legs has been tuned to 25s and is therefore out of range of wave excitation forces.

**Irregular Waves** The second solution has also been run in an irregular sea state to be able to quantify the reduction in dynamic response in a condition that is similar to a real-life storm. The results are given in the following table:

 Table 8-3:
 DAFs comparison between regular and flexible leg-hull connection for irregular sea state

Model	BSH	OTM
A120P	1.82	2.38
A120P - Flex	0.98	0.92

Both Dynamic Amplification Factors for the model with flexible leg-hull connection are below unity. This means that the dynamic response of the system is smaller compared to its quasistatic response. The inclusion of inertia effects has actually reduced the response, whereas in most other situation this inclusion leads to an increased response. The harmonic excitation is applied to the legs. Since the hull is decoupled by the flexible connection between the two it absorbs the movement of the legs like a damper would. The natural period of the hull is large with respect to that of the three connected legs which is the reason for this dampening action.

#### 8-2-2 Verdict

The increased flexibility of the leg-hull connection will have no impact on the environmental loads acting on the structure and will not add a large amount of weight to the structure. A decreased stiffness between the leg and hull will however result in large relative movements between the two. This poses an engineering challenge as it is a connection which transfers a large vertical load (that of the hull) into the legs as well. Similar to the verdict of solutions 1, the introduction of a flexible leg-hull connection positively influences the dynamic response of the system but leads to challenges in other parts of the Jack-Up design.

#### 8-3 Solution 3 - TMD

Solutions 1 and 2 involved moving the dynamic response peak away from high energy wave periods. Solution 3 attempts to decrease the peak by introducing additional damping using a Tuned Mass Damper (TMD). TMD's have been used in different kinds of industries most are most known for their use in high-rise buildings that are located in earthquake prone areas. They have also been used in some offshore structures.<sup>1</sup> An example of use in an offshore structure is given in the figure below (Figure 8-7):



**Figure 8-7:** Offshore platform with installed TMD to reduce vibration due to wave loads. TMD is located at top left corner and has a mass of 27 tons (vs 525 tons of total platform weight).

A tuned mass damper consists of a mass, connected to the primary system by springs and dampers. The characteristics  $(m_a, k_a \text{ and } c_a)$  of these three elements are chosen such that the auxiliary system will decrease the dynamic response of the main system. In this application, the main system is the Jack-Up itself and the TMD would be connected to for instance the hull. A schematic representation is given in the following figure (Figure 8-8):



Figure 8-8: Jack-Up with TMD

<sup>&</sup>lt;sup>1</sup>http://www.flow-engineering.com/projects/production%20platform/

**TMD Parameter Selection** The parameters of the TMD dictate its possible effect on the dynamic response of the structure. Tuned Mass Dampers are tuned to approximately match the natural frequency of the system they are connected to. Due to a phase shift their response will reduce the response of the main system however.

Simple expressions can be used to get first estimates of the TMD parameters which will reduce the dynamic response of the main system at its natural frequency [Reed, 2002]:

Using

 $\alpha = \omega_a / \omega_0$  $\mu = m_a / m_0$ 

In which subscript a indicates the auxiliary system and subscript 0 indicates the main system (Jack-Up).

The optimal value for  $\alpha$  is given by:

$$\alpha_{opt} = \frac{1}{1+\mu} \tag{8-3}$$

This gives us the desired value for  $\omega_a$  which can be used to determine the required stiffness  $k_a$  of the TMD (using SDOF theory).

Finally the desired damping is found using:

$$\zeta_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)^3}}$$
(8-4)

These equations were used to design a TMD for model A in a water depth of 120m with pinned foundation. TMD's become more effective when  $\mu$  increases. The limits for the mass of the TMD are structural and often lie at around 10% of the mass of the primary system. In the case of a Jack-Up this gives a mass of approximately 1500 tons. The natural period of the model in this configuration is 11 seconds, which leads to the following parameters selected for the TMD:

Table 8-4: TMD parameters for A120P model

Danamatan	Value	Unita
Parameter	value	Units
$m_a$	1600	[tons]
$\mu$	0.1	[-]
$\alpha_{opt}$	0.909	[-]
$\omega_a$	0.519	[rad/sec]
$k_a$	431E + 3	[N/m]
$\zeta_{opt}$	0.168	[-]
$c_a$	278E + 3	[Ns/m]

#### 8-3-1 Dynamic Response



**Figure 8-9:** Daf spectrum with and without TMD for the A120P model. Inclusion of the TMD clearly shows reduction of the DAF peak for the model without TMD. Two new (lower) peaks have formed at periods slightly above and below the natural period of the original model.

Figure 8-9 shows the single peak for the system without TMD has changed into a series of two peaks, one slightly lower and one slightly higher than the original peak. This demonstrates the effect of the TMD as it is designed to decrease the original DAF peak. The maximum DAF for OTM and BSH have decreased by roughly 30%, which is a significant gain in terms of the Jack-Up assessment.

#### 8-3-2 Verdict

The problem inherent in the use problem of tuned mass dampers is their suitability for only a small range of excitation periods. Jack-Ups are exposed to a wider range of excitation periods due to the irregular nature of sea states and the variance of the significant wave periods of different storms. The TMD also increases amplification at periods above or below the tuned period and can therefore increase dynamic response for certain excitation periods. The fabrication of a TMD with a mass of approximately 10% of the structure is also challenging with respect to Jack-Ups as the inclusion of a 1500 ton TMD will mean the variable load capacity of the unit will reduce accordingly.

#### 8-4 Solution 4 - Coupled Floater

Solution four consists of an externally floating sphere which is connected to the Jack-Up. The resulting dynamic system is shown below (Figure 8-10):



Figure 8-10: Schematic of externally floating sphere coupled to Jack-Up.

#### 8-4-1 Sphere properties

For simplicity the sphere is assumed to be completely filled. Furthermore, the liquid inside the sphere is restricted from movement by anti-sloshing plates which are installed in the inside of the body. The fluid is therefore assumed frozen (solid) in the dynamic response analysis that follows. The following properties are obtained for the floating sphere:

•  $m_s$  - The mass of the sphere is given by the volume and density of the fluid it holds and is given by:

$$m_{sphere} = \rho \cdot \frac{4}{3}\pi R^3 \tag{8-5}$$

•  $I_{\phi\phi}$  - The rotational moment of inertia of a solid sphere is given by:

$$I_{\phi\phi} = \frac{2}{5}mR^2 \tag{8-6}$$

•  $a_{11}$  - The added mass in surge/sway direction is given by:

$$m_{11} = \pi \rho R^2 \tag{8-7}$$

Furthermore the sphere does not offer any restoring forces in neither surge/sway nor roll direction.

#### 8-4-2 Dynamic Response

The coupled floater system can not be implemented into the USFOS model since the program does not support floating bodies and their dynamics. For this reason the equations of motion are derived analytically to be solved using MATLAB afterwards. The system will be solved by modelling it as a SDOF system first, after which an 2DOF analysis will also be performed.

#### **SDOF Approach**

An SDOF approach similar to the one used to estimate the natural periods of Jack-Ups in Section 6-1-1 can be used to estimate the natural period of the system under consideration. Fixation of the floater in x,y and z direction reduces the problem to a single degree of freedom:



Figure 8-11: SDOF Jack-Up and coupled floating sphere

Lagrangian's formulation of the Equations of Motion can be used to set up the equation that describe the dynamics of the system.

The Lagrangian is defined as:

$$\mathcal{L} = T - V \tag{8-8}$$

And the equation of motion for every j:

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{q}_j}\right) - \frac{\partial \mathcal{L}}{\partial q_j} = Q_j \tag{8-9}$$

The kinetic energy of the system is given by:

$$T = 1/2m_1\dot{w_1}^2 + 1/2I_{\phi\phi}\dot{\phi}^2 \tag{8-10}$$

Using the small angle approximation we can state that:

$$tan\phi \approx \phi = \frac{w_1}{d} \tag{8-11}$$

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Combination of Eq. (8-10) and Eq. (8-11) gives:

$$T = 1/2m_1 \dot{w_1}^2 + 1/2 \frac{I_{\phi\phi}}{(d+R)^2} \dot{w_1}^2$$
(8-12)

The potential energy of the system is given by:

$$V = 1/2k_1 w_1^2 \tag{8-13}$$

This gives the Lagrangian:

$$\mathcal{L} = 1/2 \left( m_1 + \frac{I_{\phi\phi}}{(d+R)^2} \right) \dot{w_1}^2 - 1/2k_1 w_1^2$$
(8-14)

We now calculate the following derivatives:

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{w_1}}\right) = \left(m_1 + \frac{I_{\phi\phi}}{(d+R)^2}\right) \ddot{w_1}$$
(8-15)

$$\frac{\partial \mathcal{L}}{\partial w_1} = -k_1 w_1 \tag{8-16}$$

Adding externally acting forces and energy dissipation due to damping we obtain the EoM:

$$\left(m_1 + \frac{I_{\phi\phi}}{(d+R)^2}\right)\ddot{w}_1 + k_1w_1 = -c\dot{w}_1 + F_W$$
(8-17)

The equation of motion describes the SDOF approximation of the problem under consideration. It can be used to calculate the natural period of the system. Ignoring damping, the natural frequency  $\omega_n$  is given by:

$$\omega_n = \sqrt{\frac{k_1}{m_1 + \frac{I_{\phi\phi}}{(d+R)^2}}}$$
(8-18)

#### Jack-Up to Floater connection

The connection between the two systems forms an important part of the nature of the response of the system as a whole. The floater will be excited by wave loads which will cause it to move both in the vertical and the horizontal plane. Decoupling this motion from the rest of the system will prevent the floating body from adding excitation to the system. For that reason a sliding connection between the connecting rod and the floater is proposed as it will decouple the heave motion of the floater and will also allow it to move in the horizontal plane without causing excitation to the rest of the system. Some kind of stiffness is required to be added to the floater (either at the floater to Jack-Up connection or a mooring system):



Figure 8-12: Jack-Up to floater connection design

#### **2DOF Approach**

The system shown in Figure 8-12 has two independent degrees of freedom  $w_1$  and  $w_2$ . The angle  $\phi$  can be expressed in terms of the two independent degrees of freedom.

Again, using the Lagrangian formulation of the EoM:

For j = 1: The kinetic energy of the system is given by:

$$T = \frac{1}{2}m_1 \dot{w_1}^2 + \frac{1}{2}I_{\phi\phi}\dot{\phi}^2 \tag{8-19}$$

Using the small angle approximation we can express  $\phi$  as a function of  $w_1$  and  $w_2$ :

$$T = \frac{1}{2}m_1 \dot{w_1}^2 + \frac{1}{2}I_{\phi\phi} \left\{\frac{\dot{w_1} - \dot{w_2}}{d}\right\}^2$$
(8-20)

And the potential energy in the system can be described as:

$$V = \frac{1}{2}k_1 w_1^2 \tag{8-21}$$

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This gives the Lagrangian:

$$\mathcal{L} = \frac{1}{2}m_1 \dot{w_1}^2 + \frac{1}{2}I_{\phi\phi} \left\{\frac{\dot{w_1} - \dot{w_2}}{d}\right\}^2 - \frac{1}{2}k_1 w_1^2$$
(8-22)

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{w_1}}\right) = \left(m_1 + \frac{I_{\phi\phi}}{d^2}\right)\ddot{w_1} - \frac{I_{\phi\phi}}{d^2}\ddot{w_2}$$
(8-23)

$$\frac{\partial \mathcal{L}}{\partial w_1} = -k_1 w_1 \tag{8-24}$$

Adding externally acting forces and energy dissipation due to damping we obtain the first EoM:

$$\left(m_1 + \frac{I_{\phi\phi}}{d^2}\right)\ddot{w}_1 - \frac{I_{\phi\phi}}{d^2}\ddot{w}_2 + k_1w_1 = -c\dot{w}_1 + F_{W_1}$$
(8-25)

For j = 2: Using a similar procedure as used above, we find:

$$\left( \left( m_2 + a_{11} \right) + \frac{I_{\phi\phi}}{d^2} \right) \ddot{w}_2 - \frac{I_{\phi\phi}}{d^2} \ddot{w}_1 = -b_{11} \dot{w}_2 + F_{W_{2,sway}}$$
(8-26)

The equations of motion for both degrees of freedom can be combined to give the following system of equations:

$$\begin{bmatrix} m_1 + \frac{I}{d^2} & -\frac{I}{d^2} \\ -\frac{I}{d^2} & (m_2 + a_{11}) + \frac{I}{d^2} \end{bmatrix} \begin{bmatrix} \ddot{w}_1 \\ \ddot{w}_2 \end{bmatrix} + \begin{bmatrix} c_1 & 0 \\ 0 & b_{11} \end{bmatrix} \begin{bmatrix} \dot{w}_1 \\ \dot{w}_2 \end{bmatrix} + \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} = \begin{bmatrix} F_{W_1} \\ F_{W_{2,sway}} \end{bmatrix}$$
(8-27)

The system given by Eq. (8-27) can be used to determine the required radius R of the sphere to achieve the desired natural periods of the system. MATLAB can be used to solve the eigenfrequency problem given by:

$$det\left(\left[K\right] - \lambda\left[M\right]\right)v = 0 \tag{8-28}$$

Eq. (8-28) gives the natural frequencies (and hence periods) of the undamped system for free vibration. This was used to give the following plot which relates the sphere radius R and the natural periods of the system:



**Figure 8-13:** Natural periods of 2DOF system for varying sphere radius. Black line indicating 20s period boundary.

The goal of adding the floater is to reduce the dynamic response of the system. This can be achieved by increasing the natural periods of the system above 20s as this is the upper limit of the periods of high energy waves. This limit is indicated in the figure above by a black line. The sphere radius needs to be greater than approximately 40 meters in order to achieve natural periods this high.

#### 8-4-3 The Verdict

The use of an externally floating sphere in order to create an inertia-dominated system is not effective. Simple 2DOF analysis has demonstrated that the sphere radius would need to exceed roughly 40m in order to effectively increase the natural periods of the system in an attempt to reduce dynamic excitation due to wave forces. Such a large sphere will experience high wave loads which need to be accounted for by a large and heavy mooring system.

The solution above attempts to create an inertia-dominated system. Since the current design philosophy is based on a stiffness-dominated system using an external floater to add stiffness to the system might be more successful. Large barges are readily available in the industry. The spring coefficient for roll of a  $100 \times 40$  meter barge with a draft of 1 meter is in the order of 5E9 Nm which is an order of magnitude higher than the stiffness of a typical Jack-Up Jack-Up. The mass added to the system will however have an opposing effect on the system dynamics. Furthermore, the wave loading on the barge will have a negative impact on the behaviour of the system. The external floater in general remains an interesting, out of the box solution. A more detailed study which includes wave loads can give a more definite answer on the question whether such a system would work.

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### **Conclusions & Recommendations**

#### 9-1 Conclusions

Modern Jack-Ups are characterised by large triangular hulls, housing three spacious truss legs. Rack-chocks allow the use of slender bracing which in turn enables rig designers to use larger chord spacing without drastically increasing wave loads. The long, slender bracing connecting the chords is prone to buckling during jacking operations. For this reason RPD has become more problematic in recent years.

Larger wind areas increase the wind loads on the structure, while increased chord spacing leads to higher hydrodynamic loads. However, greater leg spacing reduces the effect of the latter and hence we find that wind loads play a more dominant role within the assessment of modern Jack-Ups when compared to older designs. This is an interesting conclusion for the following reason. The calculation of wind loads in bottom founded offshore structures is often done using the conservative projected-area method. Since wind loads often account for no more than 15% of total loading on a bottom founded structure, this has no significant impact on the assessment of the structure in question. But as wind loads become more governing in the assessment of deep water Jack-Ups, the conservative projected-area methodology places a large unnecessary burden on the assessment of the structure.

Various non-linearities associated with the dynamics of Jack-Ups were identified. This justifies the need for time-domain analysis. DAFs for BSH/OTM range from 1.2/1.4 for nonconservative modelling (full spudcan fixity) to 2.3/2.8 for conservative modelling (no spudcan fixity). The difference between these two extremities indicates the need for accurate fixity input. Furthermore, the significant dynamic amplification shows the importance of preventing an increase in natural period as water depths increase. This illustrates a dilemma within current Jack-Up design; increasing chord spacing reduces dynamic response, but increases risk of RPD. Due to the non-linear nature of the dynamic system, time-domain runs are required for every specific combination of Jack-Up, soil and MetOcean combination in an SSA. The  $T_p/T_n$  ratio can however provide first estimates for the dynamic amplification to be expected in the system. Current design philosophy is aimed at achieving natural periods below those of high energy waves. The resulting system is stiffness dominated. This reduces dynamic excitation and therefore also the movement of and loads on the structure and its foundation. A significant increase in leg stiffness is required in order to keep the system stiffness dominated when water depths increase. This is limited however to approximately 200m of water depth due to the following reasons:

- Chord Spacing: Increasing chord spacing is effective at producing high stiffness legs, but also leads to longer braces which are more susceptible to buckling as a result of RPD during jacking operations.
- Chord Area: The cross-sectional areas of chords partially determine the bending stiffness of the leg. Current production methodology is however bounded by the rolling limits of thick steel plates.

Several solutions, aimed at reducing the dynamic response were investigated. Curved legs effectively reduce the natural periods and therefore the dynamic response of the system. However, the bending moments experienced in the legs make the solution impractical. Introducing flexibility to the leg-hull connection and interconnecting the legs is a more promising solution. The dynamic response of the now separated system is significantly lower than that of the legs and hull rigidly connected. The large vertical loads that are transferred from the hull to the legs impose an engineering challenge to the design of the connection. The application of a TMD is not an effective way of reducing the dynamic response of a Jack-Up. It is only effective for a small range of excitation periods and increases response slightly above and below the initial resonance period. Furthermore, a large TMD mass is required to effectively decrease response at the resonance peak. An external floater is an "out-of-the-box" solution that will involve adding wave loads to the system. Using a floating sphere to create an inertia-dominated system is unrealistic, since the radius of the sphere needs to exceed 40 meter in order to effectively reduce the dynamic response of the total system. The use of an externally floating barge to create a more stiffness-dominated system is a more propitious solution. Although no quantitative study was carried out in this thesis, a relatively standard barge  $(100 \times 40 \text{ meters})$  adds significant stiffness to the system, possibly reducing natural periods and therefore the dynamic response due to wave loading.

#### 9-2 Recommendations

The scope of this thesis was limited to Jack-Ups in elevated condition. No research was done on the afloat condition of the rigs. These may become governing as water depths increase. This is caused by the relatively high CoG generated by long legs protruding into the air. More interesting however, is the recent struggle the industry has been having with RPD during jacking operations. This phenomenon seems to occur more often with modern rig designs due to large chord spacing and slender braces. Additionally, more and more Jack-Ups are being installed at sights where previous spudcan footprints exist. Rack Phase Difference has seen little research and is not mentioned in the guidelines. Qualitative research has been published on this matter, but quantitative studies remain absent. The way RPD grows during jacking operations and the effectiveness of different methods to counteract RPD are an interesting topic of research.

The increased presence of wind loads within environmental loads strengthens the need for accurate calculation of the former. CFD simulations and/or wind tunnel experiments on various rig designs are recommended as well as measurement campaigns to validate results. Such research can allow for lower design loads in the assessments of Jack-Ups. This allows for a reduction of the required pre-loads and hence decreases failure rates for Jack-Ups.

Spudcan fixity has been recognized to have a large impact on the dynamic response characteristics of the system. Therefore, it has been widely investigated for pre-millennium rig designs. Fixity values for modern rigs have not been analysed yet. This calls for the need of measurement campaigns to be performed on the newer rigs in deeper water. This benchmarking method will also allow for other aspects of the Jack-Up model to be validated. 

## Equivalent Hydrodynamic Properties F&G JU2000E

									VIIV	0.474	0.738	0.362	0.474	0.045	0.239	0.474	0.045	0.239	3.09												
									Div71/s	0.220	0.082	0.188	0.220	0.188	0.082	0.220	0.188	0.082	c_De		Γ										
									-		4	H	1	1	4	1	1	4													
									Reta	06	33	0	06	0	33	06	0	33													
									Alnha	30	60	60	60	30	30	30	30	30													
									v	8.50	8.50	8.50	8.50	8.50	8.50	8.50	8.50	8.50													
								N	_	8.50	7.81	13.10	8.50	13.10	7.81	8.50	13.10	7.81			i*!_i*n	1.47	1.25	2.18	1.47	1.25	2.18	1.47	1.25	2.18	1.73
										$^{}$	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48			n	1	1	4	1	1	4	1	1	4	A_e
									D iv7	0.22	0.09	0.12	0.22	0.12	0.09	0.22	0.12	0.09		LATION	A_i	0.17	0.10	0.07	0.17	0.10	0.07	0.17	0.10	0.07	
ATION	Di^2*I/s	0.220	0.188	0.082	1.48				iq	0.47	0:30	0.35	0.47	0.35	0:30	0.47	0.35	0:30		C_M CALCU	s	8.50	8.50	8.50	8.50	8.50	8.50	8.50	8.50	8.50	
D_e CALCUI	-	ĉ	ŝ	12	D_e				id J	1.50	1.00	1.00	1.50	1.00	1.00	1.50	1.00	1.00				8.50	13.10	7.81	8.50	13.10	7.81	8.50	13.10	7.81	
				I					C Dei	0.47	0.18	0.36	0.47	0.05	0.06	0.47	0.05	0.06			i d	0.47	0.35	0:30	0.47	0.35	0:30	0.47	0.35	0:30	
1ARY	1.48	3.09	4.59	1.73	2	0.0125	00.00		c	Chord	X-Brace	Hor. Members	Chord	X-Brace	Hor. Members	Chord	X-Brace	Hor. Members				Chord	X-Brace	Hor. Members	Chord	X-Brace	Hor. Members	Chord	X-Brace	Hor. Members	
SUMN	D_e	C_De	D_e*C_De	A_e	C_Me	Marine Growth	Mom. Inertia		Flow Direction	Plane 1			Plane 2			Plane 3						Plane 1			Plane 2			Plane 3			

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B

## A120P model file

''MODEL.FEM ,\_\_\_\_\_\_ 'HYDRODYNAMIC PARAMETERS ,\_\_\_\_\_\_ HYDROPAR BuDiam 1.36 Mat 1 ADDMBEAM 1200 1200 0 'Cd Cm HYD\_CDCM 0.9 0.17 ,\_\_\_\_\_ 'MODEL ,\_\_\_\_\_ ' BOW LEG x y z BC NODE 101 28.9 0.0 0.0 NODE 102 28.9 0.0 10.0 NODE 103 28.9 0.0 20.0 NODE 104 28.9 0.0 30.0 NODE 105 28.9 0.0 40.0 NODE 106 28.9 0.0 50.0 NODE 107 28.9 0.0 60.0 NODE 108 28.9 0.0 70.0 NODE 109 28.9 0.0 80.0 NODE 110 28.9 0.0 90.0 NODE 111 28.9 0.0 100.0 NODE 112 28.9 0.0 110.0 NODE 113 28.9 0.0 120.0 NODE 114 28.9 0.0 130.0 NODE 115 28.9 0.0 140.0

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```
NODE 116 28.9 0.0 150.0
  NODE 117 28.9 0.0 160.0
''NODE 118 28.9 0.0 0.0
''NODE 119 28.9 0.0 0.0
''NODE 120 28.9 0.0 0.0
''NODE 121 28.9 0.0 0.0
''NODE 122 28.9 0.0 0.0
''NODE 123 28.9 0.0 0.0
''NODE 124 28.9 0.0 0.0
''NODE 125 28.9 0.0 0.0
' PORT LEG
NODE 201 -14.43 25.00 0.0
. . .
' STAR LEG
NODE 301 -14.43 -25.00 0.0
. . .
' HULL
NODE 1001 0 0 138.0
. . .
' JACKING HOUSES
NODE 1014 35.80 0.00 140.00
. . .
' ELEM ID np1 np2 material geom lcoor ecc1 ecc2
' BOW LEG
  BEAM 101 101 102 1 1
  BEAM 102 102 103 1 1
  BEAM 103 103 104 1 1
  BEAM 104 104 105 1 1
  BEAM 105 105 106 1 1
  BEAM 106 106 107 1 1
  BEAM 107 107 108 1 1
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## **Interview Summary - GustoMSC**

#### Jack-Ups are often described as structures that see significant dynamic excitation due to the fact that their 1st mode natural periods lie close to the period of high energy waves, can GustoMSC confirm this statement?

Shallow water Jack-Ups have natural periods up to 6 seconds. Deepwater JAck-Ups will have natural periods slightly higher, say 8 to 9 seconds. Although engineers might expect higher dynamic amplification, we also see that the higher water depths increase the periods of high waves. The increase in natural period is therefore accompanied by an increase in wave period for high energy incoming waves. These effects balance out which means the DAF values from dynamic response analysis for the deeper water Jack-Ups are actually similar or close to the DAF values found for older (shallow water) Jack-Ups.

Another important factor to consider is that SNAME guidelines stipulate use of pinned foundation conditions to calculate DAFs. This inherently leads to higher DAFs then those experienced by in-situ rigs. The dynamic fixity we typically see in our rigs is around 80%. This leads to a significant reduction of the natural period and therefore in turn lowers the DAFs.

What limits the current design philosophy from going into even deeper water? The major problems that come into play when extrapolating current design philosophy to even greater depths are financial issues and production problems:

• Financial: Jack-Ups are relatively cheap compared to semi-subs when used in shallow waters. However, as we move to deeper water the semi-sub design stays very similar, but the Jack-Up needs to increase in size (and steel) rapidly to accommodate longer legs and large OTM resistance. This means that as we exceed 500' of water depth the Jack-Up solutions starts to approach similar production costs as for instance semi-subs. Without a cost advantage over other MODU solutions there is no longer a drive to design Jack-Ups for deeper waters.

• **Production:** The fabrication of Jack-Ups involves building the truss legs. These consist of split tube chords that are situated at each corner of a leg. The fabrication process of these chords involves rolling thick steel plate to form the split tube. This process becomes exceedingly difficult as Jack-Ups get larger since the thickness of the steel plate also increases (> 100mm). Production facilities are limited to the maximum steel thickness they can successfully roll to make up the chords. This will in turn limit the production of the current design philosophy.

Rack Phase Difference has shown to be problematic, especially in the newer rig designs which employ large chord spacing. How does GustoMSC cope with this structural problem? RPD can indeed become problematic if not accounted for in the leg design of a deepwater Jack-Up. One of the reasons why RPD is also increasing is because a large number of Jack-Ups nowadays operate in locations that show footprints from previous rigs.

GustoMSC increases the thickness of its diagonal bracing in order to reduce RPD. This in turn leads to heavier legs which causes higher bending moments at the bottom of the leg during transit. To resolve this problem, modern GustoMSC designs employ slightly stronger chord design at the bottom of the Jack-Up legs.

**Concluding remarks** GustoMSC foresees no problems with its ultra deep water rig designs that will be able to operate in harsh environments in water depths ranging up to 150m. The development of skirted spudcans further increases the fixity of the foundation which benefits both dynamic response and the results of a push-over test.

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# Glossary

#### List of Acronyms

BSH	Base Shear
DAF	Dynamic Amplification Factor
FEM	Finite Element Method
JIP	Joint Industry Project
кс	Keulagan-Carpenter
MODUs	Mobile Offshore Drilling Units
ОТМ	Overturning Moment
RPD	Rack Phase Difference
RSD	Relative Standard Deviation
SDOF	Single Degree of Freedom
SNAME	Society of Naval Architects and Marine Engineers
SSA	Site Specific Assessment
TMD	Tuned Mass Damper
USFOS	Ultimate Strength for Offshore Structures