Examination of Hull Forms for an Offshore Nuclear Plant

by

Randall Thomas Jagoe

B.S., SUNY Maritime College (2007)

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degrees of

Naval Engineer

and

Master of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2017

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Department of Mechanical Engineering

May 12, 2017

Signature redacted

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Thesis Supervisor

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Accepted by ..........................................

Rohan Abeyaratne

Chairman, Committee on Graduate Students
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Abstract

The Nuclear Science and Engineering Department at MIT has a concept design for an Offshore Nuclear Plant (ONP). This project highlights the advantages of the offshore location by reducing the risk of natural disasters and cost of terrestrial nuclear power facilities. The original ONP conceptual design consists of a large cylindrical floating platform similar to existing platforms in the offshore oil and natural gas industries.

This study investigates the advantages and disadvantages of different hull forms that the ONP may use in an effort to identify an optimal balance between hull configuration and stability. Multiple platform designs were modeled to compare the differences in seakeeping and stability. These variants explored the characteristics and combinations of flat hull plating to replace the original cylinder shape, lengthening the platform to minimize overall depth and draft. The different hulls were modeled and then analyzed using a three dimensional radiation-diffraction panel method to simulate each platform’s response in a given sea state. The variants were compared utilizing the JONSWAP spectrum for a 100-year storm in North Sea and evaluating the response in six degrees of freedom. While seakeeping performance is the primary characteristic evaluated, other effects of the design changes such as mooring complexity, ease of construction, and arrangeable area were also compared.

The key trade off is the seakeeping performance prediction versus the estimated economic benefits of the alternate hull form arrangement. This consideration has to be made with respect to the actual meteorological and ocean conditions for the operational location. This is particularly true with respect to ocean depth, as the deep draft of the vertically arranged hulls can allow for greater non-linear effects on the motions. For the environment specified in this study and the economic benefits perceived by the design, the laterally arranged “stretched” design is worthy of more attention.

Thesis Supervisor: Jacopo Buongiorno
Title: TEPCO Professor and Associate Department Head, Nuclear Science and Engineering
Acknowledgments

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I would also like to thank Professor Michael Golay for his advice and input over the course of the last year. Additionally, I extend my sincere gratitude to Carl van Hooijdonk (HOMAR BV), Paolo Minelli, Jared Conway, and Yaoli Zhang for their patience and assistance.

Lastly, this would not have been possible without the assistance, understanding, and sense of humor of my 2N program colleagues.
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Chapter 1

Introduction

1.1 Background

The Massachusetts Institute of Technology (MIT) Department of Nuclear Science and Engineering has developed a concept design for an Offshore Floating Nuclear Power Plant (OFNP)[8]. The advantages of this concept rely on the benefits of placing nuclear-powered electrical power generation at sea. This allows for an almost infinite heatsink, alternate and more economical construction methods, and a quicker return to the natural environment of the host location.

The initial OFNP design was based on a cylindrical floating platform design pioneered by SEVAN Marine and that is currently used in the offshore oil and natural gas industry. The initial hull design as a Floating Production and Storage and Offloading (FPSO) platform lends itself to a large interior volume that can host the nuclear power generation equipment required by the OFNP.

This cylindrical floater based design is described in detail in two previous MIT theses. The first [8], authored by Mr. Jacob Jurewicz, describes the overall OFNP concept, general layout, and construction advantages. The second thesis [12], by Mr. Matthew Strother, describes the hydrostatic and seakeeping response of the cylindrical OFNP.

The OFNP project presented two versions of the concept: a small 300 megawatt platform and a larger 1100-megawatt platform. Both sizes are based off of the SEVAN Marine FPSO designs.
1.2 Problem Statement

The cylindrical hull shape of the OFNP as originally presented is an attractive design. To reach the required size to contain the nuclear island, the platform design was extended vertically. This presents some complications that are not present in the base SEVAN design:

- Increased draft, limiting platform placement and transport
- Vertical integration during construction
- Altered seakeeping performance from the original design
- Placement of high-speed turbines or other motion-sensitive machinery at the top of the moving platform

1.3 Purpose and Scope

This study will examine some alternate hull configurations that attempt to mitigate some of the above factors. While hull shape can have significant effects on many aspects of a
design, this study will focus on the seakeeping performance of the platform.

Chapter two provides a brief theoretical background in hydrostatic and wave theory. Key in this discussion will be the definition of terms used to relate the analysis conducted.

Chapter three describes the physical location and environment utilized in the analysis. This description will include the wave spectrum, wind, and current information.

Chapter four describes the method and modeling tools used to analyze the different hull variants.

Chapter five provides a description and basis for the different hull configurations that were examined as well as contains the analysis and results of the different hull variants previously described.

Chapter six describes the conclusions of this study, recommendations, and specific items that would benefit from future work.
Chapter 2

Theoretical Background

This chapter provides a brief theoretical background in hydrostatics and hydrodynamics in order support later discussion. Key in this discussion are the definition of terms used to relate the analyses conducted.

In the interest of time and space, the reader is invited to review the hydrostatic and hydrodynamic principles, such as potential flow, that this study is based on. Faltinsen’s *Sea Loads on Ships and Offshore Structures* [5] and J.M.J. Journée’s *Offshore Hydrodynamics* [7] are excellent resources.

2.1 Hydrostatics

Previous research on the cylindrical OFNP hulls showed that they were hydrostatically stable [12]. Both Mr. Strother’s work and this study rely on the weight estimations described in the Mr. Jurewicz’s thesis [8]. These initial values result in a statically stable platform which allows this study to focus on the dynamic response of the platform in a seaway.

2.2 Motions of a Floating Platform

The motions of a floating structure can be described as rigid-body system with six degrees of freedom. These are shown in Figure 2-1.
2.3 Hydrodynamic Analysis Methods

The MOSES analytical software used in this study allows for three different methods of calculating hydrodynamic data.

Strip Theory utilizes conformal mapping of hull sections to estimate the vessel’s motions of heave, pitch, and roll. This method is only applicable to “slender” vessels (i.e. a length much greater than the beam or draft, and the beam is much less than the wavelength) and is not applicable to the hull form variations considered by this study.

Morison’s Equation calculates the viscous drag of the platform motions, but does not account for the radiation damping of the platform.

Three Dimensional Diffraction Theory considers only radiation damping, but not viscous effects. In order to account for viscous drag, some Morison’s Equation attributes must be defined.
2.4 Frequency Response Analysis

Analysis in the frequency domain allows for a linear approximation to the equations of motion. This is done by calculating the platform’s response to unit amplitude waves and linearizing the equations of motion for each wave. The output of this process is the Response Amplitude Operator (RAO), a transfer function that allows for the use of different spectra to determine approximations for the motions of the platform.

The RAOs only allow for an approximation of the response to wave frequency excitation and neglect the effect of wind or slow drift wave excitation[4].

2.5 Time Domain Analysis

A time domain analysis allows for the simulation of the platform in a specified environment. The analytical software uses the hydrodynamic data forces previously calculated, combines them with any other forces acting on the system (such as wind or current), and integrates the non-linear equations of motions in the time domain[4].
Chapter 3

Environment

3.1 Location

The concept of the OFNP allows for the ability to take advantage of the fact that the Earth's surface is 70% water. In order to minimize electrical power transmission losses, it is expected the OFNP operates approximately 6 - 12 nautical miles from shore. This allows the OFNP to be within the internationally recognized territorial waters of the host nation.

In an effort to limit the scope of analysis, a single location and environmental criteria was applied to the model. This also allows for an "apples to apples" comparison between the platform hull variants.

The location chosen was the Huntington Oil Field, located in the central North Sea approximately 205 km east of Aberdeen, Scotland. Due to the oil and gas industry presence in the area, this part of the world has a significant database of ocean and weather historical information to draw on.

3.2 Criteria

The environmental criteria utilized for the analysis was the statistical 100-year storm in the Huntington Field area of the North Sea. The data were used by SEVAN Marine to evaluate
the original cylindrical OFNP hull designs [11]. The storm is broken up into components for wind speed and profile, current speed and profile, and wave spectrum.

3.3 Wind

The wind characteristics for the 100-year storm is a speed of 34.80 m/s (67.65 knots). The model utilized the American Bureau of Shipping wind profile, shown below in 3-2 during the analysis [2]. This profile accounts for the variation in wind force over the height of the platform model above the waterline.

In the interest of a conservative “worst-case” estimate of platform motions, the direction of the wind was fixed at a heading of 180 degrees. In reality, the wind direction is not a constant heading, but this method allows for the wind heeling force to compound with the wave and current direction.
3.4 Current

The current characteristics for the 100-year storm is a speed 0.67 m/s (1.3 knots). As with the wind profile, the direction of current was fixed at 180 degrees. Additionally, the current velocity profile is constant with depth. Due to the relatively shallow depth of the model environment and the size of the platform hull variants, this is a conservative method that allows for the maximum current force on the platform hull.

3.5 Depth

The water depth at the model location is 90 m. This is also the mean value of depth for the North Sea.

3.6 Waves

The 100-year storm waves are modeled with an irregular sea spectrum for the conduct of this study. The JOint North Sea WAve Project (JONSWAP) wave spectrum is designed for coastal areas where there is limited fetch[3]. Fetch is the defined as the "spatial extent of the
body of water exposed to the wind" [10]. Equation 3.1 shows the mathematical construction of the spectrum[4]. The MOSES analysis software requires the inputs listed in Table 3.1 to build the spectrum, which is shown in Figure 3-3.

\[
S(\omega) = \alpha \times 172.8 \times H_S^2 \times z \times \exp \left[ -1948.184 \times z \left( \frac{P}{\omega} \right) \right]
\]  

(3.1)

Where:

- \( \alpha \) is a parameter calculated to make total area under the spectrum equal to \( \frac{H_S^2}{16} \)
- \( z = \left( \frac{1}{(\omega \times T_P)} \right)^4 \)
- \( p = \gamma \exp \left( \frac{(\beta - 1)^2}{2\sigma^2} \right) \)
- \( \beta = \frac{T_P \times \omega}{2\pi} \)
- \( \sigma = 0.07 \) for \( \omega \) less than peak, 0.09 for \( \omega \) greater than peak

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_S )</td>
<td>13.70</td>
<td>meters</td>
</tr>
<tr>
<td>( T_P )</td>
<td>16.00</td>
<td>seconds</td>
</tr>
<tr>
<td>Spreading Coeff.</td>
<td>200</td>
<td>—</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>3.3</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 3.1: JONSWAP Wave Spectrum Parameters[11]
Figure 3-3: North Sea 100-year Wave Spectrum
Chapter 4

Analysis Methodology

4.1 Tools

The primary numerical tool used in this study is the MOSES Offshore Platform Design and Simulation software suite by Bentley Systems, Inc. The MOSES suite contains several software modules which may be used to develop and evaluate a design. The primary components used were the MOSES Hull Modeler and the MOSES Solver.

The MOSES Hull Modeler allows for the creation of three-dimensional models and meshes and then an easy transition of that model into the other parts of the software.

Additionally, the Rhinoceros 3D modeling software from Robert McNeel & Associates was used to generate some portions of the models as well as verify dimensions and spatial arrangements.

The MOSES Solver utilizes a proprietary language and database system specifically designed to analyze marine structures and operations[4].

4.2 Approach

This study was approached in the following steps:
1. Generate a three-dimensional model of the desired hull form using NURBS surfaces

2. Establish a center of gravity (KG) for each model

3. Generate a three-dimensional analysis mesh for each model

4. Create the environmental model

5. Assume initial hydrostatic stability for the model as a baseline

6. Calculate pressure on each mesh panel for the specified wave heading and period

7. Determine the Response Amplitude Operator RAO for each period and wave heading

8. Calculate the mean drift forces acting on the model

9. Determine the motion statistics at the center of gravity of the model

10. Develop a mooring system to fix model in seaway

11. Conduct a time domain simulation in the specified environment

Steps four through eleven were conducted through the use of a written script in the MOSES Solver language.

1. NURBS Model The Non-Uniform Rational Basis Spline, or NURBS, surface is a mathematically defined surface utilized in most three-dimensional computer-aided-drafting (CAD) software. The platform hull model was developed in the MOSES Modeler software, and the example of the OFNP-1100 hull can be seen below in Figure 4-1.

2. Center of Gravity For the cylindrical OFNP-1100 hull the original weight estimates of Jurewicz[8] and Strother[12] were utilized. This weight estimation was also used in the Octagonal hull shape due to the similar arrangement of the hulls.
For the “stretched”, or barge-like hulls the original estimate no longer applied. For this case, two different methods were used to estimate the KG.

First, a simple estimate of assuming that the KG of a similar purpose platform would maintain the proportion of KG versus overall depth and draft.

The OFNP-1100 model had a KG of 30.2 m and draft of 68 m, a fraction of 0.45. The fraction of KG to depth (100 m) was 0.30.

Using these fractions in the barge-like hulls results in a KG estimate of 22.4 m and 25.2 m respectively.

The second estimate was made using the MOSES Stability software tool. This tool allowed for the placement of the same weight groups, or items, from the OFNP-1100 model in the arrangements of the stretched model. The model was then hydrostatically balanced to the design draft. This method resulted in a KG of 27 m for those hulls. This higher KG value was used for further analysis as a more conservative value.
3. **3D Mesh Model** Once the model has been created and its weight characteristics estimated, MOSES Model can also be used to create the mesh and export the file to MOSES Solver. The OFNP-1100 mesh can be seen in Figure 4-2.

![OFNP-1100 Mesh](image)

**Figure 4-2: OFNP-1100 Mesh**

4. **Environment Model** The environment was modeled as described previously in Chapter Three.

5. **Initial Stability** The mesh model and appropriate weight model were input into the MOSES Solver at the design draft and in a zero trim / zero list condition.

6. **Calculate Pressure on Mesh Panels** Once the model is input at the stable initial position, the MOSES Solver then calculates the added inertia and damping on each panel[4]. This is conducted for a set of given frequencies (or periods) and headings that are user defined. This study used 178 periods spread from 5 seconds to 35 seconds, with more intervals at areas of high inflection.
7. **Determine the RAOS** MOSES Solver then obtains the transfer function, or Response Amplitude Operator, for the model by linearizing the equations of motion. This is done for each heading input to the Solver.

8. **Calculate the mean drift forces** When creating the pressure database in Step 6, MOSES will also generate the mean drift data. This includes the diffraction/incident potential, radiation potential, and the coriolis acceleration[4].

9. **Determine motion statistics** After the above steps are completed, which can take several hours of computational time, the model database is complete and accessible for data. The frequency response and statistics of the motion at the center of gravity of the model are then output for review.

10. **Develop a mooring system to fix model in seaway** In order to maintain the model in the active seaway during the time domain simulation, the model must be fixed. While an in-depth analysis of mooring configuration was not conducted as part of this study, some mooring configurations were reviewed [1][13] and a simplified four point mooring model was adapted to establish the initial boundary condition of the platform being held in the seaway.

    Each mooring line had a length of 550m, a diameter of 260mm, and weight in water of 0.12 kN/m. The lines were established at two points on each side of the baseline of the model (four corners) and then pre-tensioned to 1750 kN.

11. **Conduct a time domain simulation** With the model fixed in the seaway, the MOSES Solver was then utilized to conduct a time domain simulation in the specified environment for 86,400 seconds (24 hours).
Chapter 5

Description of Variants and Hydrodynamic Analysis

This section will focus on the description and purpose behind the four hull forms evaluated in this study. For the statistical motion results in the frequency domain, the summary for head seas (180 degrees) is shown with each vertically arranged model. The laterally arranged model will also show the results for beam seas (090 degrees). Units for surge, sway and heave motions are in meters. Units for roll, pitch, and yaw are degrees.

The frequency domain statistical results summarized below each model description are an estimate of the maximum motion based on the RAOs calculated. This assumes a Raleigh distribution of the peaks and applies a multiplier to the Root Mean Square (RMS) of the spectrum. These multipliers are shown below in Table 5.1[3]. Therefore the maximum given for each motion is the average of the $\frac{1}{1000}$ highest amplitudes in the spectrum.

<table>
<thead>
<tr>
<th>Value</th>
<th>Multiplier</th>
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<tr>
<td>RMS</td>
<td>1.25</td>
</tr>
<tr>
<td>Avg of $\frac{1}{3}$ Highest</td>
<td>2.0</td>
</tr>
<tr>
<td>Avg of $\frac{1}{10}$ Highest</td>
<td>3.03</td>
</tr>
<tr>
<td>Avg of $\frac{1}{1000}$ Highest</td>
<td>3.72</td>
</tr>
</tbody>
</table>

Table 5.1: RMS Multipliers for Motion Statistics

The individual RAOs for each platform are located in Appendix A.
5.1 OFNP-1100 Hull

For the purposes of this study, the OFNP-1100 hull from SEVAN Marine’s OFNP Mooring and Motions Study was recreated in the modeling environment[11]. This was used as a baseline performance indicator to compare the alternate hull forms against. The hull model is shown below in Figure 5-1. Additionally, Table 5.3 lists the particulars of the OFNP-1100 model.

Figure 5-1: OFNP-1100 Hull

<table>
<thead>
<tr>
<th>Length&lt;sub&gt;WL&lt;/sub&gt;</th>
<th>75</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>75</td>
<td>m</td>
</tr>
<tr>
<td>Depth</td>
<td>100</td>
<td>m</td>
</tr>
<tr>
<td>Draft</td>
<td>68</td>
<td>m</td>
</tr>
<tr>
<td>Displacement</td>
<td>439493</td>
<td>tonnes</td>
</tr>
<tr>
<td>KG</td>
<td>30.2</td>
<td>m</td>
</tr>
</tbody>
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Table 5.2: Hull Particulars for OFNP-1100
Table 5.3 below shows the motion statistics at the center of gravity for the OFNP-1100 model.

<table>
<thead>
<tr>
<th>OFNP-1100</th>
<th>Surge</th>
<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
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<tbody>
<tr>
<td>RMS</td>
<td>1.7</td>
<td>—</td>
<td>0.9</td>
<td>—</td>
<td>0.3</td>
<td>—</td>
</tr>
<tr>
<td>Avg of 1/3 Highest</td>
<td>3.5</td>
<td>—</td>
<td>1.9</td>
<td>—</td>
<td>0.7</td>
<td>—</td>
</tr>
<tr>
<td>Avg of 1/10 Highest</td>
<td>4.4</td>
<td>—</td>
<td>2.4</td>
<td>—</td>
<td>0.9</td>
<td>—</td>
</tr>
<tr>
<td>Avg of 1/1000 Highest</td>
<td>6.4</td>
<td>—</td>
<td>3.5</td>
<td>—</td>
<td>1.3</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 5.3: Summary of OFNP-1100 Frequency Domain Motion Statistics (Head Seas)

5.2 Octagonal Hull

The first iteration of the OFNP-1100 hull design was to square off the design to an octagon. This design iteration was inspired by Mr. Carl van Hooijdonk[14] as an iterative step between the cylindrical OFNP-1100 hull form and the stretched octagonal hull form below.

The advantage of the octagonal hull form are a slight increase in arrangeable area over the cylindrical hull and a reduced construction complexity due to not requiring additional plate forming after the initial plate cutting. This can reduce time as the shipyard rollers, line heaters, or hydraulic presses will not be a bottleneck. There are possible advantages in minimizing the complexity of the welds when joining the flat plates, as well[9].

<table>
<thead>
<tr>
<th>Length&lt;sub&gt;WL&lt;/sub&gt;</th>
<th>75</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>75</td>
<td>m</td>
</tr>
<tr>
<td>Depth</td>
<td>100</td>
<td>m</td>
</tr>
<tr>
<td>Draft</td>
<td>68</td>
<td>m</td>
</tr>
<tr>
<td>Displacement</td>
<td>428316</td>
<td>tonnes</td>
</tr>
<tr>
<td>KG</td>
<td>30.2</td>
<td>m</td>
</tr>
</tbody>
</table>

Table 5.4: Hull Particulars for Octagonal Hull

Table 5.5 below shows the motion statistics at the center of gravity for the octagonal hull model. As expected, these motions are very similar to the predicted motions of the original OFNP-1100 hull.
Figure 5-2: Octagonal Hull

<table>
<thead>
<tr>
<th>Octagonal Hull</th>
<th>Surge</th>
<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>1.7</td>
<td>—</td>
<td>1.0</td>
<td>—</td>
<td>0.4</td>
<td>—</td>
</tr>
<tr>
<td>Avg of $\frac{1}{3}$ Highest</td>
<td>3.4</td>
<td>—</td>
<td>2.0</td>
<td>—</td>
<td>0.9</td>
<td>—</td>
</tr>
<tr>
<td>Avg of $\frac{1}{10}$ Highest</td>
<td>4.4</td>
<td>—</td>
<td>2.6</td>
<td>—</td>
<td>1.1</td>
<td>—</td>
</tr>
<tr>
<td>Avg of $\frac{1}{1000}$ Highest</td>
<td>6.4</td>
<td>—</td>
<td>3.7</td>
<td>—</td>
<td>1.6</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 5.5: Summary of Octagonal Hull Frequency Domain Motion Statistics (Head Seas)

5.3 Stretch Oval Hull

The second iteration of the OFNP-1100 hull design was another iterative step between the cylindrical OFNP-1100 and the stretched octagonal hull form discussed below. This is a stretched circle/oval hull that allows for the benefits of greater arrangeable area that the elongated hull supports. As the nuclear island is the heaviest component of the design as well as the most complex, the elongated hull form allows for construction or emplacement of components lateral rather than the vertical arrangement of the OFNP-1100. Additionally, this reduces both the draft and overall height of the platform. This has the benefits of allowing a greater range of locations for both construction and operations. With a lower
draft of 50 m, the elongated platform can benefit from access to/from more shipyards as well as increasing the number of shipyards that can handle building modules that tall. With the ONP concept of operations of being with territorial waters, the shallower draft allows for greater flexibility in mooring locations as well.

![Stretch Oval Hull](image)

**Figure 5-3: Stretch Oval Hull**

<table>
<thead>
<tr>
<th>Hull Particulars for Oval Stretch Hull</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length$_{WL}$</td>
</tr>
<tr>
<td>Beam</td>
</tr>
<tr>
<td>Depth</td>
</tr>
<tr>
<td>Draft</td>
</tr>
<tr>
<td>Displacement</td>
</tr>
<tr>
<td>KG</td>
</tr>
</tbody>
</table>

Table 5.6: Hull Particulars for Oval Stretch Hull

Table ?? below shows the motion statistics at the center of gravity for the Stretch Oval hull model. The Stretch Oval model has significantly more pitch and heave motion than the vertically arranged hull models in head seas. In beam seas, however, while the heave and sway motion are similar to heave and sway in head seas, there is minimal roll for the Stretch Oval hull model.
The final hull from variant is a combination of the Octagonal hull and Stretch Oval hull, as suggested by Mr. Carl van Hooijdonk[14]. This hull form was designed to take advantage of the construction efficiencies of the flat plate octagonal shape and the lateral arrangement of the stretch hull shape.

<table>
<thead>
<tr>
<th>Hull Particulars for Octagonal Stretch Hull</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong>&lt;sub&gt;WL&lt;/sub&gt;</td>
</tr>
<tr>
<td>Beam</td>
</tr>
<tr>
<td>Depth</td>
</tr>
<tr>
<td>Draft</td>
</tr>
<tr>
<td>Displacement</td>
</tr>
<tr>
<td>KG</td>
</tr>
</tbody>
</table>

5.4 Stretch Octagonal

The final hull from variant is a combination of the Octagonal hull and Stretch Oval hull, as suggested by Mr. Carl van Hooijdonk[14]. This hull form was designed to take advantage of the construction efficiencies of the flat plate octagonal shape and the lateral arrangement of the stretch hull shape.

<table>
<thead>
<tr>
<th>Summary of Stretch Octagonal Hull Frequency Domain Motion Statistics (Beam Seas)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stretch Octagonal Hull</strong></td>
</tr>
<tr>
<td>RMS</td>
</tr>
<tr>
<td>Avg of $\frac{1}{3}$ Highest</td>
</tr>
<tr>
<td>Avg of $\frac{1}{10}$ Highest</td>
</tr>
<tr>
<td>Avg of $\frac{1}{1000}$ Highest</td>
</tr>
</tbody>
</table>

Table 5.10: Summary of Stretch Octagonal Hull Frequency Domain Motion Statistics (Head Seas)
Figure 5-4: Octagonal Stretch Hull

<table>
<thead>
<tr>
<th>Stretch Octagonal Hull</th>
<th>Surge</th>
<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>—</td>
<td>1.7</td>
<td>2.5</td>
<td>0.5</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Avg of $\frac{1}{4}$ Highest</td>
<td>—</td>
<td>3.3</td>
<td>4.9</td>
<td>1.1</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Avg of $\frac{1}{10}$ Highest</td>
<td>—</td>
<td>4.2</td>
<td>6.3</td>
<td>1.3</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Avg of $\frac{1}{1000}$ Highest</td>
<td>—</td>
<td>6.2</td>
<td>9.2</td>
<td>2.0</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 5.11: Summary of Stretch Octagonal Hull Frequency Domain Motion Statistics (Beam Seas)

5.5 **Time Domain Simulation**

The OFNP-1100 cylindrical hull form and the Stretch Octagonal hull form were both subjected to 24 hours of the North Sea statistical 100-year storm. Time domain analysis takes into account the non-linear factors such as wind and current, as well as the sea spectrum. Table while Table 5.13 shows the Octagonal Stretch hull response. Units for surge, sway and heave motions are in meters. Units for roll, pitch, and yaw are degrees. Positive values are forward of the center of the ship or to starboard.
Once the non-linear components such as wind and current are applied in the time domain simulation, the limited motion characteristics of the vertically arranged OFNP-1100 hull form give way to large oscillation in pitch. This is due to the large underwater area (deep draft) affected by the current as well as the significant sail area (air draft) above the waterline. With an average of 15.7 m of bottom clearance throughout the 24 hours of simulation, the deeper draft of the OFNP-1100 may also be interacting with the relatively shallow bottom resulting in the larger heave result.

### 5.6 Summary

Table 5.14 below shows the comparison of the maximum expected results in the frequency domain analysis. As these were calculated with no mooring, that addition in both mooring cable drag and resistance may account for the difference between the unmoored frequency response and the moored, non-linear, time domain results.

<table>
<thead>
<tr>
<th>Hull Variant</th>
<th>Surge</th>
<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFNP-1100</td>
<td>6.4</td>
<td>—</td>
<td>3.5</td>
<td>—</td>
<td>1.3</td>
<td>—</td>
</tr>
<tr>
<td>Octagonal 1100</td>
<td>6.4</td>
<td>—</td>
<td>3.7</td>
<td>—</td>
<td>1.6</td>
<td>—</td>
</tr>
<tr>
<td>Stretched Cylinder</td>
<td>5.9</td>
<td>—</td>
<td>14.5</td>
<td>—</td>
<td>17.5</td>
<td>—</td>
</tr>
<tr>
<td>Stretched Octagon</td>
<td>5.5</td>
<td>—</td>
<td>8.6</td>
<td>—</td>
<td>15.2</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 5.14: Summary of Frequency Domain Maximum Motion Statistics (Head Seas)
Chapter 6

Conclusion and Recommendations

6.1 Conclusion

This study shows that there is room in the design tradespace of a hull for the ONP. Unfortunately, there is no one hull shape that is ideal for all conditions - otherwise all offshore structures and ships would look the same. As Figures 6-1 and 6-2 illustrate, the vertically arranged hull forms have an increased heave response in the frequency range of 0.24 rad/s though 0.25 rad/s, while the barge-like hulls have their pronounced response at 0.27 rad/s though 0.28 rad/s.

In summary, the longer hull form with less draft is more susceptible to greater pitch motions in a sea spectrum with a lower period (higher frequency), while the vertically arranged, deeper draft, hulls will have a larger heave response in a spectrum with a higher period (lower frequency).

The key trade off is the seakeeping performance prediction versus the estimated economic benefits of the alternate hull form arrangement. This consideration has to be made with respect to the actual meteorological and ocean conditions for the operational location. This is particularly true with respect to ocean depth, as the deep draft of the vertically arranged hulls can allow for greater non-linear effects on the motions. For the environment specified in this study and the economic benefits perceived by the design, the laterally arranged
Figure 6-1: Comparative Heave RAOs

Figure 6-2: Comparative Pitch RAOs

"stretched" design is worthy of more attention.
6.2 Issues

In comparing the motion results of this study with previous work of a similar nature, this study has produced a larger magnitude of predicted motions than other work. Afriana’s research of the SEVAN S400 FPSO[1], SEVAN’s analysis of the smaller OFNP-300[11], and the Research Partnership to Secure Energy for America (RPSEA) examination of the SEVAN 1000[13] all examined cylindrical floater hulls. While these studies focused on only one hull and (in some cases) had access to proprietary design information, they all produced motion results of a smaller magnitude.

One reason for this difference in modeling may be in the implementation of Morison’s Equation in the models. Each of the above studies used a different software tool and had access to the appropriate viscous damping information for the platform for Morison’s Equation to be applied in their study. Unfortunately, the time constraints of this study prevented a detailed analysis of viscous damping for the hull variants. The results of this study are still applicable and valuable to compare the relative behavior of different hull forms in the same seaway.

6.3 Future Work

Recommendations for further study include the following:

• Tow tank testing of a scale model of the cylindrical hull form and barge-like hull. This will allow for the physical verification of numerical studies of platform motions.

• A quantifiable assessment of construction techniques for the barge-like hull form. This could allow for a determination if an advantage in constructibility and arrangeable area outweigh the increased motions that the longer platform is susceptible to.

• The Offshore Nuclear Plant should identify a possible location for platform operations. This will allow for both the application of specific meteorological data and simulations.
• Identify a specific hull form and conduct a detailed design of the non-nuclear, platform-specific characteristics. Sizing of tank capacities, location of weights and moments, and identifying structural requirements would allow for a more accurate estimate of the platform size and initial hydrostatic parameters.

• A study of existing regulations in the International Associations of Classification Societies (IACS) to identify appropriate construction and operational guidelines for the ONP Project.
Appendix A

Figures

A.1 Response Amplitude Operators
Figure A-1: Response Amplitude Operators for the OFNP-1100 Hull in Head Seas.
Figure A-2: Response Amplitude Operators for the OFNP-1100 Hull in Beam Seas.
Figure A-3: Response Amplitude Operators for the Octagonal Hull in Head Seas.
Figure A-4: Response Amplitude Operators for the Octagonal Hull in Beam Seas.
(a) Stretch Oval Hull Surge RAO in Head Seas

(b) Stretch Oval Hull Heave RAO in Head Seas

(c) Stretch Oval Hull Pitch RAO in Head Seas

Figure A-5: Response Amplitude Operators for the Stretch Oval Hull in Head Seas.
Figure A-6: Response Amplitude Operators for the Stretch Oval Hull in Beam Seas.
(a) Stretch Octagon Hull Surge RAO in Head Seas

(b) Stretch Octagon Hull Heave RAO in Head Seas

(c) Stretch Octagon Hull Pitch RAO in Head Seas

Figure A-7: Response Amplitude Operators for the Stretch Octagon Hull in Head Seas.
(a) Stretch Octagon Hull Heave RAO in Beam Seas    (b) Stretch Octagon Hull Sway RAO in Beam Seas

(c) Stretch Octagon Hull Roll RAO in Beam Seas

Figure A-8: Response Amplitude Operators for the Stretch Octagon Hull in Beam Seas.
Appendix B

Validation

Validation for the MOSES results has previously been shown in comparison tests by J. Ray McDermott Engineering, LLC[6]. In that study, MOSES was compared to the WaveAnalysisMIT (WAMIT) software package. WAMIT is the most widely used and well-proven three-dimensional diffraction and radiation program in the frequency domain. In particular, Strother’s research on the ONP hull forms was conducted using WAMIT[12] as well as additional Master’s thesis by Afriana[1].

McDermott used a three-dimensional mesh of five different models to compare the results of the MOSES and WAMIT numerical calculations. As an example, one of the models is shown below in Figure B-1.

The cylinder model has the following characteristics:

- Length: 200.0 m
- Beam: 40.0 m
- Draft: 40.0 m
- Displacement: 256011.0 mt
- Center of Gravity: 200.0 m
- Number of Panels: 1120
The results of the cylinder model comparison are shown in Figure B-2 through Figure B-5.

McDermott concludes that the comparison of MOSES with WAMIT shows good agreement.
Figure B-2: Cylinder Added Mass
Figure B-3: Cylinder Damping
Figure B-4: Cylinder Wave Excitation
Figure B-5: Cylinder RAOS
Bibliography


[14] Carl van Hooijdonk. Request for model of stretched octagonal hull. E-mail to OFNP research group on 19 Jan 2017.