Conceptual design of a floating support structure for an offshore vertical axis wind turbine: the lessons learnt

M COLLU, F P BRENNAN, M H PATEL

Offshore, Process, and Energy Engineering Department, Cranfield University, Cranfield, UK

Maurizio Collu (corresponding author), Whittle Building, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK. maurizio.collu@cranfield.ac.uk, T: +44 (0)1234 75 4779

Feargal P. Brennan, Whittle Building, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK. f.brennan@cranfield.ac.uk, T: +44 (0)1234 75 8249

Minoo H. Patel, Building 83, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK. minoo.patel@cranfield.ac.uk, T: +44 (0)1234 75 4769

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The design of floating support structures for wind turbines located offshore is a relatively new field. In contrast, the offshore oil and gas industry has been developing its technologies since the mid 1950s. However, the significantly and subtly different requirements of the offshore wind industry call for new methodologies. An Energy Technologies Institute (ETI) funded project called NOVA (for Novel Vertical Axis wind turbine) examined the feasibility of a large offshore vertical axis wind turbine in the 10 to 20 MW power range. The development of a case study for the NOVA project required a methodology to be developed to select the best configuration, based on the system dynamics. The design space has been investigated, ranking the possible options using a multi-criteria decision making (MCDM) method called TOPSIS. The best 'class' or design solution (based on water plane area stability) has been selected for a more detailed analysis. Two configurations are considered: a barge and a semisubmersible. The iterations to optimise and compare these two options are presented here, taking their dynamics and costs into account. The barge concept evolved to the 'triple doughnut-Miyagawa' concept, consisting of an annular cylindrical shape with an inner (to control the damping) and outer (to control added mass) bottom flat plates. The semisubmersible was optimised to obtain the best trade-off between dynamic behaviour and amount of material needed. The main conclusion is that the driving requirement is an acceptable response to wave action, not the ability to float or the ability to counteract the wind turbine overturning moment. A simple cost comparison is presented.

Keywords: offshore wind, floating support, conceptual design, dynamics

1 Introduction

1.1 Context and problem statement

Over recent decades, the need for further clean and renewable energy, together with substantial developments in the technology, has driven the increasing size and power of wind turbines: currently they are reaching the limits of land based-sites[1]. Current 'offshore' wind farms can be better defined as 'near-shore', being deployed in relatively shallow water (average water depth ~15 m, and 30 - 40 m max), but the trend is to move to farther and deeper sites. A similar phenomenon has already been observed in the offshore oil and gas industry: drilling in deeper waters became both technically feasible and economically advantageous, and several types of offshore support structures for oil rigs were developed, evolving from bottom-fixed to floating concepts.

Research on floating support structures for offshore wind turbines is still in its pre-commercial phase. The first scaled and full scale prototypes have been deployed and studied in recent years (Hywind, by Statoil; Submerged Deepwater Platform, by Blue H). A number of promising concepts have been developed and are going to be tested through preliminary experimental campaigns (Aerogenerator X, by a consortium led by Cranfield University; Vertiwind, by Technip & Nenuphar-Wind; DeepWind, by a consortium led by Risø DTU Technical University of Denmark; Nautica Windpower

[1] See fig.2-6, p. 29, "20% Wind Energy by 2030, Increasing Wind Energy's Contribution to U.S. Electricity Supply", DOE/GO-102008-2567, July 2008

AFT, WindFloat, by WindPlus+Vestas; Sway Turbine, by Sway; Winflo, by Nass & Wind, etc.).

The number and variety of concepts proposed is a clear indication of the relative novelty of this research field and the need for further work. This is demonstrated by , the multiple research programmes, funded by governments and private companies all around the world, investigating possible floating support structures.

The aim of the present work is to illustrate the methodology developed for the conceptual design of a floating support structure for a very large vertical axis offshore wind turbine, focusing on how the geometrical and inertial characteristics influence the dynamic response to waves.

2 Methodology

2.1 Design space investigation

The oil & gas offshore industry has developed several floating (or at least mobile) support structure concepts, such as tension leg platform (TLP), semi-submersible vessels, self-elevating jack-up platforms, single point moorings, SPARs, and others. Some of these can be re-utilised and adapted to the offshore wind energy industry, and a simple way to classify them has been proposed by Wayman et al. (2006). This classification is based on the method used to achieve static stability with respect to the rotational degrees of freedom. There are three ways to achieve stability for a floating structure:

- through waterplane area (buoyancy variation with angle of heel),
- through ballast to modify the Centre of Gravity,
- through tensioned vertical tendon lines.

A detailed description of each class is illustrated by authors in [3]. Another classification method has been proposed in the standard DNV-OS-J101 issued by DNV (2007).

2.2 Floating support structure ranking: TOPSIS method

In (Kolios et al. 2010), a methodology to choose the optimum structure has been presented, based on a multi-criteria decision making (MCDM) method, called TOPSIS. The criteria against which each structure has been evaluated are: capacity to support axial loads, to resist overturning moment, to resist torsion, compliance, durability, ease of installation, maintainability, environmental impact, likely cost, carbon footprint, certification and site depth. Results in (Kolios et al. 2010) show that, among floating support structures, a waterplane stabilised structure presents the best overall score.

The main advantages are: long durability, relative ease of installation, optimal maintainability, together with its low environmental impact and low cost in comparison with the other floating options. Another important advantage is the possibility to deploy the barge in very shallow sites (around 30 m). An operating life of 30 to 50 years is achievable without any major technical challenge, due to the possibility to perform major maintenance service operations (around every 5-7 years) onshore or near-shore, quicker and at lower cost. In addition, the topside can be coupled with the support structure onshore or near-shore, avoiding costly offshore operations with specialised vessels that, at the present time, can have a waiting time of months due to their limited availability.

Barges have the shallowest draught with respect to all other support structure options, limiting the environmental impact to the effect of the catenary mooring system. These aspects and its structural simplicity can result in lower cost with respect to other floating options.

The main disadvantages are linked to its large waterplane area: wave loads are proportional to this characteristic. A semisubmersible configuration has been chosen to lessen this problem.

2.3 Design and analysis methodology

Based on a literature review on floating support structures analysis, the necessary steps to analyse a floating support structure are basically four: preliminary sizing, static analysis, dynamic analysis of the structure, and, summarising all previous steps, the concept evaluation (Figure 1).

In the first step, taking into account basic input data about the rotor and the drive train, and fulfilling basic requirements, the main geometrical and inertial characteristics of the floating structure configuration are derived. The aerodynamic loads acting on the VAWT in these conditions have been calculated with an in-house aerodynamic performance model, based on Paraschivoiu's Double-Multiple Streamtube (DMST) model. It relies on blade element momentum (BEM) theory, the standard approach for the wind industry, and also includes also Gormont's dynamic stall model with corrections proposed by Masse and Berg, as well allowances for wind shear, tip, junction and tower losses. In the second step, a hydrostatic analysis is performed, and the equilibrium state is derived. In the third step, a hydrodynamic analysis is performed, taking into account the dynamic characteristics of the floating structure, of the rotor and of the drive train, as well as the site characteristics (wave spectrum, water depth, etc.).

Iterating through these three steps, a configuration is developed, and the concept can be evaluated, marked and compared with other configurations. This methodology has been illustrated in detail in (Collu et al. 2010).

2.4 Axis system and design environmental conditions

The reference offshore wind turbine system is composed of a vertical axis rotor (arms, sails, hub, and turntable), a drive train (generator, gear box, ancillary systems), and a floating (or fixed) support structure. This system experiences rigid body motions in the standard six degrees of freedom, three translational and three rotational. The coordinate system, as shown in Figure 2, consists of a right-handed orthogonal axis system, where the:

- *x* axis is parallel and in the same direction as the wind main direction,
- *z* axis is the vertical axis, positive upward,
- *y* axis according to x and z directions.

Following this definition, the forces and moments are:

- $\mathbf{F_1}$, $\mathbf{F_2}$, and $\mathbf{F_3}$, respectively surge, side (or sway) and heave force,
- $\mathbf{F_4}$, $\mathbf{F_5}$, and $\mathbf{F_6}$, respectively roll, pitch and yaw moment.

The origin of the axis system is taken as the x and y locations of the floating support structure's centre of gravity, and the z = 0 plane coincides with the calm water surface.

The system of equations of motion, in the rigid-body framework, is:

$$(\mathbf{M} + \mathbf{A})\boldsymbol{\eta}'' + \mathbf{B}\boldsymbol{\eta}' + \mathbf{C}\boldsymbol{\eta} = a\boldsymbol{x}e^{i\omega t} \quad (1)$$

where $\boldsymbol{\eta}(\mathbf{t})$ is the 6 by 1 vector describing the system's translational and rotational displacements, and $\boldsymbol{\eta}'$ and $\boldsymbol{\eta}''$ respectively its first and second derivative with respect to the time (respectively velocities and accelerations), **M** the 6 by 6 mass matrix, **A** the 6 by 6 added mass matrix, **B** the 6 by 6 damping matrix, **C** the 6 by 6 restoring matrix (called also stiffness matrix). On the right hand side, the waves' forces experienced by the turbine are represented, where a is the wave amplitude, ω is the wave frequency and $\boldsymbol{x}$ is the 6 by 1 vector of exciting forces and moments on the system.

If the linear theory is adopted, with regular, plane progressive waves, the displacements, velocities and accelerations can be written as follows:

$$\boldsymbol{\eta} = \mathrm{Re}\left\{\boldsymbol{\xi}\mathrm{e}^{\mathrm{i}\omega t}\right\} \tag{2}$$

$$\boldsymbol{\eta'} = \mathrm{Re}\left\{\mathrm{i}\omega\boldsymbol{\xi}\mathrm{e}^{\mathrm{i}\omega t}\right\} \tag{3}$$

$$\boldsymbol{\eta''} = \mathrm{Re}\left\{-\mathrm{i}\omega^2\boldsymbol{\Xi}\mathrm{e}^{\mathrm{i}\omega t}\right\} \tag{4}$$

and, substituting into the previous equation, the system of equations of motion illustrating the response of the system (as a rigid body) to regular, plane progressive waves is:

$$\left[-\omega^2\left(\mathbf{M} + \mathbf{A}(\omega)\right) + i\omega\mathbf{B}(\omega) + \mathbf{C}\right]\boldsymbol{\xi}(\omega) = \boldsymbol{x}(\omega) \tag{5}$$

2.5 Design Environment

A design environment has been established. Wind, wave and current conditions have been specified based on typical conditions of UK, in round three, zone four sites (Table 1). The JONSWAP wave spectrum formula is illustrated, and values of its parameters are shown in Table 1.

3 Design and analysis I: from cylindrical/square barge to the ‘triple doughnut’ barge

3.1 Introduction

Even if the floating structure configuration space has been narrowed down to waterplane area stabilised structures, there are very many possible structural configurations. In this and the next sections how and why the floating structure configuration evolved from a simple cylindrical barge to the final semisubmersible is explained.

3.2 Barge configuration I: cylindrical/square barge

The first and simplest configuration consists of a cylinder, with radius R, draught d, freeboard H_f, as illustrated in Figure 3. The structure can be in steel or concrete, and the drive train system (gear box plus generators) can be included in the upper section of the body.

The driving parameter, from a static stability point of view, is the minimum rotational stiffness. For this reason, the buoyancy given by this structure exceeds by far the minimum buoyancy required: it is necessary to add a seawater filled ballast tank at the bottom of the cylindrical barge to have the desired draught and freeboard height. This ballast material can also be concrete. This tank lowers the *CG* vertical position, with a beneficial effect to the radius.

In fact, for this structure rotational stiffness is given by:

$$C_{44,55} = F_B z_{CB} - M_{tot} g z_{CG} + \rho_{SW} g \pi \frac{R^4}{4} \tag{6}$$

The main contributor is the second moment of the waterplane area, driven by R^4. If CG is below the waterline, z_{CG} is negative, and the weight moment term is positive. The lower the *CG*, the smaller the radius *R* for the same rotational stiffness.

To have an idea of the order of magnitude of the radius necessary, with the hypothesis that the difference $F_B * z_{CB} - M_{tot} * g * z_{CG}$ is small compared to the waterplane area contribution, the minimum radii required for the NOVA 5 MW and 10 MW offshore wind turbines systems (full cylinder configuration in steel plus seawater filled ballast tank) are illustrated in Table 3.

3.2.1 Dynamic analysis

As regards dynamic analysis, three cylindrical and three square barge configurations have been investigated and compared, in order to derive heave, roll and pitch natural frequencies. At this stage, in order to ensure a higher robustness of the solution, three possible rotor and drive train dimensions and weights have been estimated (Table 4), and for each one both a cylindrical and a square barge have been sized. Dynamic analyses results are presented in Table 5.

The reference JONSWAP wave spectrum (Table 2) has a circular peak frequency of around 0.628 rad s^{-1}. Natural frequencies (mainly in roll and pitch) of these six configurations are near this frequency, and this should be avoided in order not to have resonance. To manage this challenge, the configuration has been changed by adding a plate at the bottom of the barge.

3.3 Barge configuration II: hollow Cylindrical/Square barge

The basic idea is similar to the first cylindrical barge design, with the difference being the central 'moonpool'. Since the second moment of the waterplane area is proportional to R^4, the external region of the cylindrical barge is giving a much greater contribution to the rotational stiffness than the almost negligible contribution of the central region.

Therefore, with a slight increase of the radius, the same minimum required stiffness is obtained, and the material utilised in the previous configuration in the central region is saved, with a beneficial effect on the final price (Figure 4).The preliminary sizing of a hollow cylindrical barge made in steel are presented in Table 6.

The amount of material needed, and therefore the cost, is proportional to the volume of the structure. Keeping the same total height (freeboard height plus draught), the cost is proportional to the waterplane area. Comparing Tables 3 and Table 6, the waterplane area of the hollow configurations are 25% and 28% less than the solid cylindrical configuration, respectively for the 5 MW and 10 MW systems, having the same stiffness coefficient.

3.3.1 Dynamic analysis

Dynamic analyses have been conducted, varying the only ‘tuning’ parameter of this configuration: the width of the ‘doughnut’. In particular, three hollow square barges have been analysed, varying the width of the doughnut: 2.5 m, 5 m, and 10 m. When decreasing the width of the hollow barge, the side length has to be increased in order to obtain the same second moment of the waterplane area. The natural frequencies of the 3 configurations I (squared, solid) ranged from 0.48 to 0.51 rad/s (heave), while those of the 3 configurations II (squared, with central moonpool) ranged from 0.93 to 1 rad/s, but with a relatively high RAO around the wave spectrum peak frequency, leading to an excessive response to wave. Therefore a new design has been studied: the ‘double doughnut’.

3.4 Barge configuration III: double doughnut configuration

The natural frequencies of the previous barge configurations were too close to the reference JONSWAP wave spectrum’s peak frequency. A hollow cylindrical (square) flat plate has been introduced at the bottom of the barge, which is an element in the configuration that can be 'tuned' to partially control the heave, roll and pitch natural frequencies obtained.

Analytically, the effect of the second doughnut can be illustrated as follows. Heave (33), pitch (55) and roll (44) natural circular frequencies are given by:

$$\omega_{33}^{*} = 2\pi\sqrt{\frac{C_{33}}{m_A+m}} \tag{6}$$

$$\omega_{44}^{*} = 2\pi\sqrt{\frac{C_{44}}{I_{44,A}+I_{44}}} \tag{7}$$

$$\omega_{55}^{*} = 2\pi\sqrt{\frac{C_{55}}{I_{55,A}+I_{55}}} \tag{8}$$

The bottom external flat plate has a double effect:

- added mass (m_A) and added moments of inertia both in roll and pitch ($I_{44,a}$, $I_{55,a}$) are augmented,
- total mass (m) and total moments of inertia ($I_{44,a}$, $I_{55,a}$) are augmented.

Both these effects contribute to lowering these natural frequencies. Natural periods ($T^*_{ii}=2\pi/\omega^*_{ii}$) are augmented.

3.4.1 Dynamic analysis

A sensitivity analysis on the influence of the second 'doughnut', the bottom external flat plate, on the natural frequencies of the structure has been performed, and the results are shown in Table 7.

The second step has been to size the circular bottom plate as it augments by 25%, 50% and 100% the added mass with respect to the baseline case, i.e. a hollow circular barge without any ‘second doughnut’. As can be seen in Figure 6, the effect of the second doughnut is to shift the peaks toward lower frequencies (beneficial), but at the same time the response amplitude is increased in heave (unwanted effect). This is due to the fact that the bottom flat plate represents an additional surface on which the underwater pressure caused by the passage of the waves acts. For the square configuration, the results are similar.

Since the pressure disturbance due to the passage of the wave diminishes exponentially with depth, a parametric analysis varying the draught of the structure has been conducted. In Figure 7 the dynamics of the four configurations analysed are illustrated, and their characteristics illustrated in Table 8: configuration A does not have a 2nd doughnut, while configurations B, C, and D possess a 2nd doughnut with a width of 10 m. The draught of the configuration is increased going from configuration B to configuration D.

Comparing A and B, the effect of adding the bottom plate (the second doughnut) is observed. Comparing B, C, and D, the effect of augmenting the draught is shown. The beneficial effect due to the exponential decrease of wave induced pressures is not big enough to counteract the increase of the total surface on which the pressure acts (by increasing the draught, the area of the vertical walls of the hull are increased).

3.5 Barge configuration IV: triple doughnut – Miyagawa configuration

As shown, increasing the draught of the floating support structure does not eliminate or lessen the second undesired effect. An observation has to be made: results in Figure 6 and Figure 7 have been obtained using a viscous damping coefficient equals to zero. As very well known, the RAO peaks can be reduced by increasing the damping ratio.

Miyagawa, Matsuura and others (Miyagawa et al. 1989 1991) (Matsuura 1995) investigated and performed experiments (on a scale model) on a novel floating structure configuration, called mono-column, with characteristics similar to the double doughnut design of the present work (Figure 8).

The main difference is in the bottom flat plate extending not only outward, but also inward. Matsuura et al. (1995) present scale model tests results, varying the geometry of the external flat bottom plate (the ‘second doughnut’) and internal flat bottom plate (the ‘third doughnut’). As regards the second doughnut, results confirm what has been shown before: this external plate can be used to augment the added mass of the floating structure, ‘tuning’ the natural frequency of the structure. In particular, by augmenting the ratio L_{HO}/L_{CO}, the added mass is augmented. Furthermore, in general (the effect depends on the frequency considered), by reducing the diameter L_{HI} the damping coefficient in heave is augmented.

3.5.1 Dynamic analysis: first part

A parametric analysis has been conducted varying the main configuration parameters: draught, L_{HO}/L_{CO}, L_{HI}/L_{CI}, and width of the water-piercing 'doughnut' (Figure 9). In total, ten configurations have been analysed, illustrated in Table 9.

For conciseness, the complete sets of results are not presented here, but it has been derived that, from a dynamic point of view, the triple doughnut floating configuration which has the best characteristics the baseline configuration. With its deep draught (25 m), the outer and inner bottom flat plates are relatively insensitive to the wave pressure disturbance; the negative effect of having an additional surface (the second and third doughnuts), leading to an RAO magnitude increase in heave and pitch, is avoided. The second doughnut shifts the RAO peaks toward lower frequencies, making the coupling between the floating structure dynamics and the JONSWAP wave spectra lower. The effects of the third doughnut should be assessed through an (scale model) experimental campaign, since they are linked with the damping coefficient of the structure. Nonetheless, it has been proved through numerical analyses that the added mass and added moments of inertia effects in heave and pitch are much lower with respect to the second doughnut. Its role is to change the damping coefficient, as illustrated in (Matsuura 1995).

As regards the width of the first doughnut, again, the baseline configuration (w =

13 m) seems to have the best value from a dynamic point of view. On the other hand, the deepest draught, the largest second and third doughnuts, as well as the largest width, make this option the most expensive.

3.5.2 Dynamic analysis: second part

Learning from previous observations, three configurations have been considered. Referring to Figure 10 and Table 10:

- configuration A: represents the cheapest option of the range investigated. It does not have any bottom flat plate (worst dynamic behaviour),
- configuration B: represents the optimum configuration from a dynamic response point of view. It possesses both the largest second and third doughnut. It is also the most expensive,
- configuration C: a 'cost-dynamic response trade-off' configuration has been developed, trying to save the material utilised (steel) without sacrificing the dynamic response of the floating support structure too much.

In Figure 11 the heave RAO and the heave response spectra, using the operational JONSWAP wave, are represented and in Figure 12 the same graphs for the pitch rotational degree of freedom are represented.

Configuration A, as expected, has the worst dynamic behaviour. Peaks' frequencies, in heave and even more in pitch are very near to the JONSWAP operational peak frequency (~0.628 rad s^{-1}), leading to the higher response spectrum. On the other hand, the most expensive configuration B possesses the lowest heave and pitch RAO, and the peaks are shifted toward low frequencies (long periods). This is reflected in the lowest heave and pitch response spectra. Configuration C presents an intermediate dynamic behaviour.

As regards the magnitude of heave and pitch RAOs, configuration C seems to have the highest values. As already said, these simulations have been performed considering a damping ratio equal to zero in all degrees of freedom, while in reality the damping ratio range is from 5% to 25% and the peaks would be lower. Furthermore, peaks are less coupled with the JONSWAP operational wave spectrum, and this is shown in the response spectra; configuration C collects much less energy from the wave spectra than configuration A, and slightly more than configuration B. To quantify the response spectra, the zero-th moment of the curve is considered. This corresponds to the square of the standard deviation (Tables 11 and 12).

For each degree of freedom, analyses have been performed for three wave directions, 0 deg (aligned with x axis in Figure 2), 45 deg, and 90 deg. The value in these tables is the maximum value among the three directions.

Configuration A presents the biggest standard deviation, while configuration B the smallest, about 2 orders of magnitude lower than A. Configuration C possesses a wave response motion around 1 order of magnitude lower than A. The significant wave response motion is equal to 2*σ, while the maximum is equal to 3.72*σ. Similar considerations apply. Configuration C, the configuration chosen for the final comparison, has a heave and pitch natural frequency around 0.425 rad/s.

4 Design and analysis II: Semisubmersible

The triple doughnut configuration can be 'tuned' to adapt to different wave spectra, changing the size of the second and the third doughnuts to influence the added mass and damping coefficients, respectively.

Similar characteristics can be also achieved with a different, and extensively used, configuration: the semisubmersible. A semisubmersible is a floating platform consisting of two main components: deeply submerged pontoons and several large-diameter columns. It is characterised by a lower wave response than a barge with similar requirements, due to the fact that a large percentage of its submerged volume is in the lowest position (pontoons), thus exploiting the exponential decay of the wave pressures with depth. Furthermore, a semisubmersible is characterised by "cancellation frequencies", i.e. frequencies at which the instantaneous forces on the pontoons are equal in modulus but opposite in direction with respect to the force acting on the columns, leading to zero net force amplitude (Patel 1989).

4.1 Configuration: general considerations

The configuration considered here has two pontoons and four columns, with sides of equal length (square). While from a structural point of view four pontoons would be better than two, from a manufacturing and maintenance point of view two pontoons are preferable. As known, the rotational (pitch and roll) degrees of freedom stiffness are given by the following expression:

$$C_{44,55} = F_B z_{CB} - M_{tot} g z_{CG} + \rho_{sw} g 4 \left(\frac{\pi}{4} r^4 + \pi r^2 d_C^2\right) \tag{9}$$

where r is the columns' radius and d_C is the distance of the columns from the centreline of the semisubmersible. Considering the sum of the first two terms to be negligible with respect to the third term, the pitch and roll rotational stiffnesses are determined by the value of the couple (r, d_C). This means that the same stiffness can be obtained with a low r and high d_C or with a large r and low d_C.

From a dynamic point of view, having columns with a large radius (r) and near each other (low d_C) is similar to having a cylindrical/square barge, leading to the same dynamics problem. On the other hand, a small radius grants a small waterplane area, leading to a reduced wave response. However, a smaller radius requires a larger d_C, and this could lead to structural problems (in the pontoons and in the structures connecting the columns).

4.2 Dynamic analysis

A parametric analysis has been performed, taking into account three configurations:

- configuration A: large r and small d_C,
- configuration B: small r and large d_C,
- configuration C: cancellation wave frequency (approx) near the JONSWAP wave spectrum frequency.

The three configurations are represented in Figure 13, and details are shown in Table 13.

In Figure 14 and Figure 15, the heave and pitch response amplitude operators and response spectra are presented.

4.3 Considerations

4.3.1 Heave

Configuration A, with its relatively large r and small d_C, is characterised by the largest response around the JONSWAP wave spectrum peak frequency (0.628 rad s^{-1}). A smaller radius and, consequently, bigger d_C lead to lower RAO around peak frequency. As for the double doughnut, the natural frequency shift is linked to an increase of the peak magnitude, but this occurs in a low energy frequency range.

Coupling heave RAOs with the JONSWAP operational wave spectrum, configuration A shows the worst behaviour, as expected. Configuration B has a very low response spectrum across the whole frequency range investigated, and configuration C possesses a response spectrum similar to configuration B, except for frequencies around 0.46 rad s^{-1}. These RAOs and response spectra can be explained by considering the length of the pontoons. The added mass of configuration A is lower than that of configuration C, and the maximum added mass is that of configuration B, due to the plan area of the pontoons. Furthermore, by augmenting the plan area, the force on the structure due to wave pressure augments, which explains the enhanced RAO magnitude.

4.3.2 Pitch

As for heave, augmenting the distance between the columns and diminishing their radius, the RAO peaks are shifted toward lower frequencies, and the peaks' magnitude are augmented. However, there is an important difference: the three configurations present a similar response to waves, since configuration A already has a pitch RAO peak frequency low enough, and in general, response spectra are considerably lower for all three structures. Quantitatively, the standard deviation, the significant wave response motion and the max wave response motion are shown in Table 14.

4.4 Final considerations

If the distance between the columns is augmented and, keeping the same rotational stiffness coefficient, their radius is diminished, a reduced heave response spectrum and a reduced amount of material needed (lower cost) will be obtained.

From a structural point of view, another analysis has been conducted. In a first iteration, the amount of material needed has been estimated assuming a bridge area of 400 m^2 and density of 950 kg m^{-2}. Actually, the material needed for the bridge augments more than linearly with the distance between the columns and, taking this into account, it has been found that the amount of material (cost) has a minimum around a certain d_C; below this value, cost is driven by the material needed for the hull, while above it the cost is driven by the material needed by the structure connecting the columns.

5 Limitations

5.1 Frequency analysis versus time domain response

The dynamic analyses adopted to design and compare the present configurations are based on a frequency domain analysis: briefly, the system wave dynamic response of the whole system is analysed in the frequency spectrum, with the aim of de-coupling as much as possible the RAO of the system from the wave spectrum, in order to minimise the wave response. The floating wind turbine system is considered a rigid body; therefore no structural dynamics have been taken into account.

At the moment, the state of the art approach would be a coupled aero-hydro-elastic-servo analysis. However, the vertical axis wind turbine characteristics that needed to be known in order to conduct this analysis were not available. Therefore, considering also the conceptual/preliminary nature of the present study, the frequency-analysis based approach adopted here seems to be most suitable at this point, recommending a more complete approach once the characteristics of the wind turbine have been defined.

6 Configuration Chosen: Semisubmersible

6.1 Dynamics comparison

In Table 15 the dynamic behaviour of the triple doughnut configuration C with the semisubmersible configuration C is compared.

In heave and in pitch, the semisubmersible C is more suitable, while in roll the two configurations are similar. Nonetheless, comparing the triple doughnut configuration B with all the semisubmersible configurations, the triple doughnut presents a better (lower) wave response.

6.2 Material and price considerations

The accuracy of the economic analysis presented here is substantially influenced by two factors: the early design phase (conceptual design) and the novelty of the project. For these reasons, only the capital expenditures have been taken into account as basis to narrow down the possible configurations for the support structure of the vertical axis wind turbine, not having enough historical data to derive a reliable estimate for the operational costs. The problem therefore is reduced to the amount of material needed and, therefore, the price. It is reasonable to assume that an extra triple doughnut configuration can be designed, with geometric characteristics in between configurations B and C, and dynamic characteristics similar to the semisubmersible configuration C. Therefore no clear winner emerges.

So far only steel has been considered, but the analysis was further developed including concrete. The preliminary sizing of four floating support structures was performed:

- triple doughnut, steel
- triple doughnut, concrete
- semisubmersible, steel
- semisubmersible, concrete

To estimate the costs, a comparative estimate has been conducted. The cost of one metric tonne of concrete has been set to 1 cost point. Based on that, the costs of the other materials have been estimated. As regards floating structures constructed from steel, the cost of typical steel used for offshore floating structures has been assumed (grade 50 steel), and the ratio between its cost and the cost of concrete has been set at 6.7. As regards concrete construction options, pre-stressed reinforced steel has been assumed, with a density of pre-stressed steel at 100 kg m^{-3} of concrete, and rebar steel's density at 180 kg m^{-3} of concrete. Pre-stressed steel cost has been set to 3.3 cost points per metric tonne and rebar steel cost at 1.7 cost points per tonne. It has to be noted that the semisubmersible concrete solution configuration is not with two pontoons but with four, due to the structural issues linked with the strength characteristics of concrete. Based on these assumptions, the cost comparison is illustrated in Table 16. The steel semisubmersible configuration seems to be the cheapest solution.

Due to the novelty of this field of research and the consequent lack of data, the range of validity of these cost estimates has to be realised, i.e. these are preliminary, approximate figures. Nonetheless, due to the fact that:

- these estimates are based on quotes from offshore floating structures manufacturers, and
- the differences in cost in Table 16 are considerable (steel semisubmersible, the

cheapest solution, is around 50% cheaper than the second cheapest solution, the steel triple doughnut),

the steel semisubmersible configuration has been chosen.

7 Conclusions

As happened with the oil & gas offshore industry, the wind industry has already moved from onshore to near-shore sites, and is now investigating possible solutions for further and deeper offshore sites. This is evidenced by the many studies produced and pilot systems deployed all around the world.

The range of depths at which a floating support option becomes economically advantageous with respect to a bottom fixed solution has been investigated in a number of studies, but has yet to be proved at full scale. Anyway, the range seems to be around 50-100 m, depending on site conditions, and beyond this would certainly seem preferable (Collu et al. 2010).

Considering the floating support structure configurations developed for the oil & gas industry, together with the new configurations designed for offshore wind turbines, it is necessary to develop a criteria to rank them according to the specific requirements; the TOPSIS methodology used (Kolios et al. 2010) is suitable for this task.

According to the requirements (mainly wind turbine characteristics and location), waterplane stabilised structures seem to be preferable, and two basic configurations of this class have been analysed, focusing on the dynamics of the system: a barge and a semisubmersible.

The main conclusion is that, in general, the requirement driving the design is a good dynamic response to waves. If only basic requirements were taken into account (ability to float and ability to counteract the wind turbine overturning moment), a much smaller, lighter, and cheaper structure would fulfil them.

The barge concept evolved from a simple cylindrical shape to the 'triple doughnut-Miyagawa' concept, consisting of an annular cylindrical shape with inner and outer flat plates, placed at the bottom of the structure. The inner 'ring', or 'doughnut', can be tuned to mainly control the system's heave damping coefficient: this is particularly useful to reduce the RAO peak. The outer 'doughnut' can be used to mainly tune the added mass coefficient in heave, and then give the ability to 'tune' the natural frequency of the system.

The semisubmersible was optimised to obtain the best trade-off between dynamic behaviour and amount of material needed, exploiting also the 'wave cancellation effect' peculiar to this particular configuration. Even if the Miyagawa concept presents the best dynamics, and considering also the cost estimate, the semisubmersible configuration seems the most preferable option.

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Appendix A: Notation

C_{ii}	[N m^{-1}, Nm rad^{-1}]	Stiffness coefficient relative to the i-th degree of freedom (heave i=3, roll i=4, pitch i=5)
CF	[m]	centre of flotation
CG	[m]	centre of gravity
d	[m]	draught
D_C	[m]	column draught
D_H	[m]	lower hull height
F_i	[N]	i=1,2,3, surge, sway, and heave force,
	[N m]	i=4,5,6 roll, pitch, and yaw moments
F_B	[N]	buoyancy force
G	[m s^{-2}]	gravitational acceleration constant (9.81 m s^{-2})
GM	[m]	metacentric height, positive if M, the metacentre, is above CG
GZ	[m]	horizontal projection of GM, for small angle GZ = GM sin(θ)
H_f, *h_f*	[m]	freeboard height, distance between the mean waterline level and the top of the floating structure
I_{ii}	[kg m^2]	moment of inertia with respect to x_i
L_{CI}	[m]	column inner diameter
L_{CO}	[m]	column outer diameter
L_{HI}	[m]	lower hull inner diameter
L_{HO}	[m]	lower hull outer diameter
m	[kg]	mass
m_A	[kg]	hydrodynamic added mass
m_{TOT}	[kg]	mass of the whole NOVA system
R	[m]	radius
RAO_i	[m m^{-1}],[m rad^{-1}]	Response Amplitude Operator, relative to i-th degree of freedom.
Rotor		Rotor system, composed of arms, sails, hub and turntable
RS		Response spectrum
T^*_{ii}	[s]	natural period, i-th degree of freedom, of the NOVA system
Tilt angle	[deg]	angle of inclination of the floating support structure under operational/survival loads
H_i	[m, rad]	i-th degree of freedom

ρ_{sw}	[kg m^{-3}]	seawater density (1025 kg m^{-3})
ω^*_{ii}	[rad s^{-1}]	i-th natural circular frequency of the NOVA system

References

Collu M, Kolios AJ, Chahardehi A, Brennan FP. 2010. A comparison between the preliminary design studies of a fixed and a floating support structure for a 5 MW offshore wind turbine in the North Sea. Marine Renewable & Offshore Wind Energy Conference; 21–23 April; RINA HQ London(UK).

DNV Det Norske Veritas. 2007. Design of Offshore Wind Turbine Structures. Norway. Report No.: DNV-OS-J101.

Kolios AJ, Collu M, Chahardehi A, Brennan FP. 2010. A Multicriteria decision making method to compare support structures for offshore wind turbines. European Wind Energy Conference (EWEC 2010); 21–23 April; Warsaw (Poland).

Matsuura M, Isozaki Y, Ishibashi Y. 1995. Development of Mono-Column Type Hull Form with Passive Type Motion Damping Devices for Floating Production System. 14th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 1995); June; Copenhagen (Denmark).

Miyagawa M, Isozaki Y, Yano S, Matsuura M. 1989. Development of New Concepts on Floating Production Storage and Offloading Unit. 8th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 1989); Netherlands.

Miyagawa M, Isozaki Y. 1991. Design of Mono-Column-Type FPSO. SPE Asia-Pacific Conference; Australia (SPE 22985).

Patel MH. 1989. Dynamics of Offshore Structures. London (UK): Butterworth & Co.

Wayman EN, Sclavonous PD, Butterfield S, Jonkman JM, Musial W. 2006. Coupled Dynamic Modeling of Floating Wind Turbine Systems. Golden (CO): NREL. Report No.: NREL/CP-500-39841.

Table 1: Wind, wave, and current design conditions

WIND		
Reference height	Top of structure	
Reference wind speed	50 m s^{-1}	Class I, 10-min
50 year return gust speed	70 m s^{-1}	Class I, 50 year
Wind profile	NWP; α=1.2	$V(z)=V(z_0)*(z/z_0)^{\alpha}$
Air density	1.225 kg m^{-3}	Standard air density (15ºC, 1 atm)
WAVE		
Average water depth	65 m	
Peak period (T_p)	10 s	Period of the dominant wave system
50 year values for H_s / T_p	10 m / 14 s	Values for worst three hours in 50 years
H_{max}	18.7 m	Max wave height in the worst three hours in 50 years
Wave spectrum	JONSWAP, γ=3.3	Typical North Sea
Seawater density	1025 kg m^{-3}	Standard seawater density (15ºC, 1 atm)
CURRENT		
Value	1 m s^{-1}	Typical value for round 3 sites
Profile	None	/

Table 2: JONSWAP spectrum parameters' value

Parameter	Value		Description
	Operational	Survival	
H_s [m]	4.928 m	10 m	Significant wave height
α	0.008074	0.008110	Phillips' constant
ω_p [rad s^{-1}]	0.628319	0.448799	Peak frequency
Γ	3.3	3.812	Peakedness
τ	0.07 $\omega < \omega_p$ 0.09 $\omega > \omega_p$		Spectral width parameter

Table 3: Cylindrical barge dimensions for the 5 and 10 MW offshore wind systems

NOVA system size	\	5 MW	10 MW
Minimum C_{ii}	Nm rad^{-1}	1.891 E+09	2.578 E+09
Minimum Diameter	M	~ 44.5	~ 48
Waterplane area	m^2	1537.2	1795

Table 4: Rotor and drive train dimensions and weights

Section	Parameter	Case 1	Case 2	Case 3
Rotor	Material	Steel	Glass fibre	Carbon fibre
	Dimensions	Height 110 m, diameter 260 m		
	Weight	1600 tonnes	300 tonnes	200 tonnes
Drive train	Dimensions	Cube, 10 m side	Cube, 8 m side	
	Weight	1500 tonnes	850 tonnes	800 tonnes

Table 5: Cylindrical and square barge dynamic analysis main results

#	Shape	Weight	Dimensions		Resonant frequencies		
		Mass	Rad.	Side	Heave	Roll	Pitch
		m	R	L	ω	ω	ω
		[tonnes]	[m]	[m]	[rad s^{-1}]	[rad s^{-1}]	[rad s^{-1}]
C-01	Circular	6966	25.6	\	0.474	0.429	0.315
C-02	Circular	7365	23.7	\	0.499	0.692	0.582
C-03	Circular	7383	23.5	\	0.502	0.742	0.647
S-01	Square	6722	\	44.9	0.480	0.433	0.480
S-02	Square	7156	\	41.4	0.505	0.697	0.585
S-03	Square	7177	\	41.1	0.507	0.748	0.651

Table 6: Cylinder with ‘moonpool’ (doughnut) dimensions

NOVA system (hollow cylinder)	u.m.	5 MW	10 MW
Min C_{ii}	Nm rad^{-1}	1.891 E+09	2.578 E+09
Moonpool diameter	m	~ 26.5	~ 31
‘Doughnut’ diameter	m	~ 46.5	~ 51
Waterplane area	m^2	1145.5	1290.5

Table 7: Double doughnut, dynamics analysis

Structure mass [tonne]	Flat plate width [m]	Resonant periods and frequencies					
		Heave		Roll		Pitch	
		T [s]	ω [rad s^{-1}]	T [s]	ω [rad s^{-1}]	T [s]	ω [rad s^{-1}]
3379	0	10.9	0.579	14.5	0.435	20.2	0.311
3774	5	12.6	0.498	18	0.348	23	0.274
4028	10	16.3	0.385	24.7	0.254	28.5	0.220

Table 8: Geometric characteristics of the configurations analysed in Figure 7

Configuration name	2^{nd} doughnut width	Draught
dL00m-d08m (A)	No 2^{nd} doughnut	8 m
dL10m-d08m (B)	10 m	8 m
dL10m-d12m (C)	10 m	12 m
dL10m-d16m (D)	10 m	16 m

Table 9: Triple doughnut configuration, parametric analysis

Parameter	Draught	L_{HO}/L_{CO}	L_{HI}/L_{CI}	width
Baseline configuration [7]	25 m	1.36	0.5	13 m
Draught analysis	15 m, 20 m	1.36	0.5	13 m
L_{HO}/L_{CO} analysis ($\varphi_{21,e}$)	25 m	1.24, 1.12, 1.00	0.5	13 m
L_{HI}/L_{CI} analysis ($\varphi_{21,i}$)	25 m	1.36	0.25, 0.75, 1.00	13 m
Width analysis	25 m	1.36	0.5	8 m, 10.5 m

Table 10: Triple doughnut final three configurations

Parameter	u.m.	Configuration A (cheapest)	Configuration B (dynamic optimum)	Configuration C (cost-dynamic trade-off)
w	[m]	8	13	8
Draught	[m]	12	25	15
R1,i	[m]	24.4	19.4	24.4
R2,i	[m]	No 3rd doughnut	9.7	18.3
$\varphi_{21,i}$	/	1.00	0.50	0.75
R1,e	[m]	32.4	32.4	32.4
R2,e	[m]	No 2nd doughnut	44.0	36.2
$\varphi_{21,e}$	/	1.00	1.36	1.12
Steel (approx)	[t]	2986	5521	3853
Ballast seawater	[t]	17727	66250	25329
Total mass	[t]	20713	71771	29182

Table 11: Final three triple doughnut configurations, heave, pitch and roll σ

DOF	u.m.	Standard deviation (σ)		
Configuration		A	B	C
Heave	[m]	1.3704	0.0515	0.7781
Pitch	[rad]	0.1550	0.0025	0.0297
Roll	[rad]	0.1685	0.0026	0.0904

Table 12: Final three triple doughnut configurations, heave, pitch and roll significant and maximum wave response amplitudes

DOF	u.m.	Significant wave response motion (2*σ)		
Configuration		A	B	C
Heave	[m]	2.7408	0.1029	1.5561
Pitch	[rad]	0.3099	0.0049	0.0594
Roll	[rad]	0.3369	0.0051	0.1809
DOF	u.m.	Max wave response motion (3.72*σ)		
Heave	[m]	5.0979	0.1915	2.8944
Pitch	[rad]	0.5764	0.0092	0.1105
Roll	[rad]	0.6267	0.0096	0.3364

Table 13: Semisubmersible three configurations data

Parameter	u.m.	Configuration A (large radius, small side length)	Configuration B (small radius, large side length)	Configuration C (dynamic-optimized)
Side length	[m]	71	108	81
Draught	[m]	12	15	15
Freeboard height	[m]	10	10	10
Pontoon width	[m]	23	11	17
Pontoon height	[m]	2	2	2
Columns radius	[m]	11.5	5.5	8.5
Steel (approx)	[t]	3386	2988	3012
Ballast seawater	[t]	23785	5637	13273
Total mass	[t]	27171	8626	16285

Table 14: Three semisubmersibles configuration analysis: heave, pitch and roll σ, 2*σ, and 3.72*σ

DOF	u.m.	Standard deviation (σ)		
Configuration		A	B	C
Heave	[m]	1.2724	0.4618	0.5893
Pitch	[rad]	0.0416	0.0085	0.0274
Roll	[rad]	0.1361	0.2136	0.1458
DOF	u.m.	Significant wave response motion (2*σ)		
Heave	[m]	2.5448	0.9237	1.1786
Pitch	[rad]	0.0832	0.0171	0.0548
Roll	[rad]	0.2722	0.4272	0.2917
DOF	u.m.	Max wave response motion (3.72*σ)		
Heave	[m]	4.7333	1.7181	2.1923
Pitch	[rad]	0.1547	0.0318	0.1019
Roll	[rad]	0.5064	0.7945	0.5425

Table 15: Triple doughnut VS semisubmersible, response spectra standard deviation

DOF	u.m.	Standard deviation (σ)	
Configuration		Triple doughnut C	Semisubmersible C
Heave	[m]	1.3704	0.5893
Pitch	[rad]	0.1550	0.0274
Roll	[rad]	0.1685	0.1458

Table 16: Triple doughnut VS semisubmersible, steel VS concrete relative cost analysis

Configuration	Triple doughnut		Semisubmersible	
Material	Steel	Concrete	Steel	Concrete
MAIN DIMENSIONS				
Freeboard height [m]	10	10	10	10
Draught [m]	15	15	15	15
Overall width [m]	81	83	70	71
Notes	\	\	2 pontoons	4 pontoons
MASS BREAKDOWN				
Steel [t]	4387	360	3027	285
Concrete [t]	\	22102	\	28285
Rebar steel [t]	\	1768	\	806
Pre-stressed steel [t]	\	982	\	417
Ballast (seawater)	30003	10650	17935	15535
Total mass [t]	34390	35863	20962	45329
COST (in cost points)	29244	30723	20183	32919