Project funded by the European Commission under the 6th (EC) RTD
Framework Programme (2002- 2006) within the framework of the specific research and technological development programme "Integrating and strengthening the European Research Area"

Project UpWind

Contract No.:
019945 (SES6)

"Integrated Wind Turbine Design"

COMPLIANT BOTTOM MOUNTED SUPPORT STRUCTURE TYPES

Deliverable WP4.2.4 Report on compliant bottom mounted support structure types

AUTHOR:	Wybren de Vries
AFFILIATION:	Delft University of Technology
ADDRESS:	Stevinweg 1, 2628 CN, Delft
TEL.:	+31 15 278 7568
EMAIL:	w.e.devries@tudelft.nl
FURTHER AUTHORS:	
REVIEWER:	F. Vorpahl
APPROVER:	J. van der Tempel

Document Information

DOCUMENT TYPE	Deliverable Report
DOCUMENT NAME:	UpWind Deliverable D4.2.4: Report on compliant bottom mounted support structure types
REVISION:	3
REV.DATE:	July 2009
CLASSIFICATION:	R0: General Public
STATUS:	S0: Approved/Released

Acknowledgements

This report is the result of work jointly carried out by several participants in Task 4.2 “Concepts for deep water sites”. Contributions from the University of Stuttgart (M. Kühn, T. Fischer), DTU/Risø (J.D. Sørensen), DONG A/S (C. Mørch), GEGR-E (P.W. Cheng), GL Wind (K. Argyriadis, B. Schmidt), RAMBOLL A/S (H.Carstens), Shell (A. Ploeg), NREL (J. Jonkman, G. Bir), GH (T. Camp, A. Cordle) and IWES (F. Vorpahl) are kindly acknowledged.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released	X		**R0**	General public	X		Private web site	
S1	Reviewed			**R1**	Restricted to project members			Public web site	X
S2	Pending for review			**R2**	Restricted to European. Commission			Paper copy	
S3	Draft for commends			**R3**	Restricted to WP members + PL				
S4	Under preparation			**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

1.1 Purpose of this document

This document is the deliverable report on compliant bottom mounted support structures types, reporting work carried out as part of UpWind work package *WP4 - Foundations and Support Structures*, subtask 4.2 – *Concepts for deep water sites*.

During the course of the past year it became apparent that for the correct analysis of new compliant structures a full integrated time domain analysis would be required to be able to determine both the ultimate limit state and fatigue loads. For this kind of analysis no program is readily available that allows the correct inclusion of the support structures with the (non-linear) boundary conditions.

Furthermore it was deemed uncertain whether the available aero-elastic models describe the response well at these low frequency ranges. The sensitivity to non-linear mean wave drift forces is also hard to determine at this stage.

Based on these considerations it was decided to consider this part of the research within WP 4.2 as exploratory, with the aim of investigating the possibilities and indicating areas of interest for further research.

1.2 Definition of compliant structures

Compliance can be defined as “degree of yielding under applied force”. Applying this definition to offshore structure implies the following definition for compliant offshore structures:

> “A compliant offshore structure is a structure in the marine environment that accommodates the (dynamic) forces by flexibility instead of resisting the loads rigidly, thereby limiting the internal (dynamic) loads.”

The remainder of this report has been written with this definition in mind.

1.3 Approach

As the compliant offshore structure concept originates in the offshore oil and gas industry, this report starts off in chapter 2 with a look into the history of compliant structures in that field of engineering. In the following chapter the theory behind compliant structures is described. Chapter 4 describes the boundary conditions of offshore compliant structures and how they can be met. Chapter 5 draws on the experience of the oil and gas industry to establish several compliant structure concepts. These concepts are different in scale and loading to the oil and gas structures and therefore the limitations of the compliant concepts for application in the offshore wind industry are explored in Chapter 6. An outlook for application of compliant structures in the offshore wind industry and recommendations for further research will be given in the ultimate chapter.

2. Overview of compliant structures in the offshore oil industry

2.1 Introduction

In the mid 1970s developments in the oil & gas industry were taking place in increasingly deep water. Particularly in the Gulf of Mexico, the traditional approach of designing bottom mounted support structures with a natural frequency higher than the prevailing wave frequencies became more and more challenging. In 1978 the Cognac platform was installed in 312 m of water depth. At the time it seemed that the depth limit was reached for fixed (steel) structures. Eventually the record set by the Cognac development was to be surpassed by the Bullwinkle platform in 1988. Standing in 412 m of water, it was a gargantuan undertaking. Building and installing this structure was extremely expensive, drawing on the largest equipment available to get it in its final position over the Manatee field. It was clear that other solutions were needed and engineers were wondering whether the support structure could be designed to be slender and flexible enough to move with the waves instead of resisting them. This resulted in a design for a guyed tower for the Lena field in the Gulf of Mexico which was installed in 1983. Plunging oil prices in the mid 1980s meant that massive projects in deep water were suddenly highly unattractive and the guyed tower concept was not to be repeated again. But the idea of the compliant tower as a more cost-effective alternative to a jacket structure in deep water lingered and was finally put to practice in 1998. In that year two compliant structures were installed. Pushing the depth record for a bottom mounted support structures to 535 m. After the Baldpate and Petronius structures no compliant towers were constructed for a decade, preference being given to floating structures for deep water developments. The compliant structure made its comeback with the construction and installation of the Benguela/Belize compliant tower off the coast of Angola. The recent installation of the compliant tower for the Tombua Landana field, again off the coast of Angola, shows that the compliant structure is still a viable solution for deep water hydrocarbon production developments.

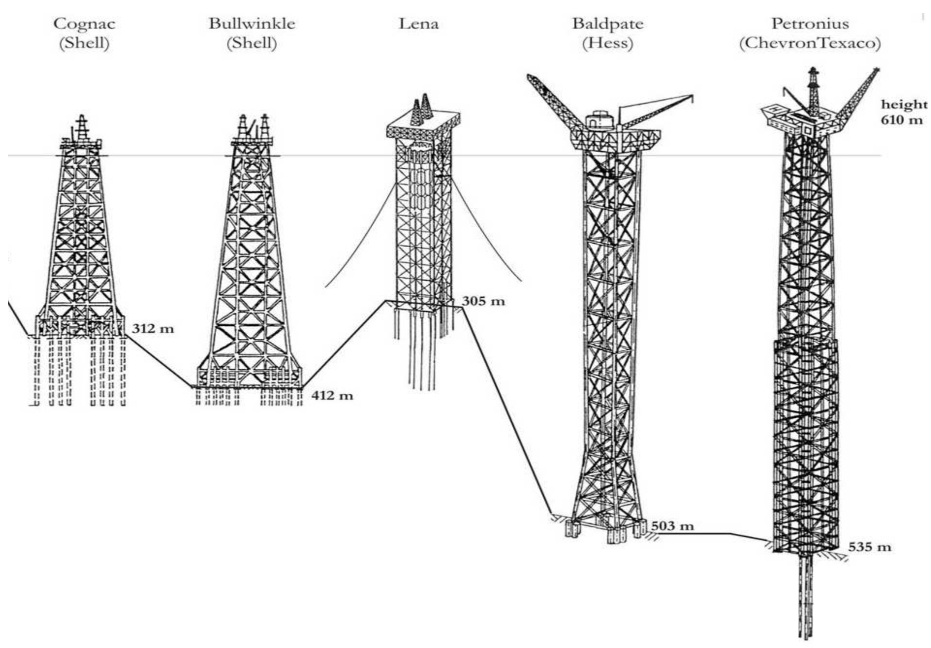

Figure 1: *Comparison of different support structures [1]*

2.2 Compliant tower projects

2.2.1 Introduction

The following sections give a brief overview of the existing compliant structures for the oil and gas industry along with key data and how the structure was made to behave in a compliant way

2.2.2 Lena guyed tower

The Lena guyed tower was engineered by Exxon for its Lena Prospect in the Mississippi Canyon. The 27 000 ton structure was designed with a ring of eight piles at the base that were located close to the tower's vertical axis to ensure sufficient bending flexibility. Further piles were applied at the corners to resist torsion. The structure was fitted with 20 guy lines that would help to transfer lateral loads to the seabed. The guy wires, connected to the top of the structure, were attached to anchor piles located at a distance of 900 m from the structure. The lines consisted of 135 mm wires, sheathed in polyethylene, and incorporated a 200 ton articulated clump weight. Under normal operational conditions the clump weights would be lying on the seabed and would thereby stiffen the system during moderate sea states. During storms, when a more flexible behaviour is required the weights would be lifted of the seabed, giving the structure a more flexible behaviour, decreasing its natural frequency away from the wave frequencies. Twelve buoyancy cans with a diameter of 6 m and a length of 36 m were incorporated in the upper part of the structure [1] [3] Table 1 lists some key data for the Lena project.

Table 1: *Key data of Lena guyed structure*

Description	Value	unit
Water depth	305	m
Topsides	4.900	ton
Support structure mass	27,000	ton

2.2.3 Baldpate

In 1998 the Baldpate platform was installed in the Garden Banks block in the Gulf of Mexico. This compliant tower consists of several sections and incorporates an articulation point that determines its dynamic behaviour.

The jacket base is 100 m tall, 42 m wide at the base and 27 m at the top, weighing 8700 tons. The tower section spans 400 m and corresponds to the top dimensions of the jacket base. It weighs approximately 20,000 tons. The structure is free standing, transferring lateral and vertical loads to the seabed through its foundation piles. To ensure sufficient flexibility an articulation point that acts as a hinge allows the upper section to be compliant under storm conditions. Figure 2 shows the structure on transport and on site with the topsides installed. Some data on the Baldpate development is presented in Table 2.

Figure 2: *Baldpate platform in place (left) [9] and tower section during transport [10]*

Table 2: *Key data of Baldpate compliant structure*

Description	Value	unit
Water depth	503	m
Natural frequency	0.033	Hz
Topsides	2,400	ton
Jacket base weight	8,700	ton
Tower section weight	20,200	ton

2.2.4 Petronius

The Petronius Compliant structure is located in the Viosca Knoll block in the Gulf of Mexico. It stands in 535 m of water and is composed of two tower sections. It is the tallest bottom mounted offshore structure ever built. The Petronius support structure has a base width of 33 m and weighs approximately 43000 tons. The structure relies on flex piles to give the structure its flexibility. The flex piles - three at each corner - are fixed to the structure only at the top of the piles and near the base. Guides provide lateral restraint at regular intermediate intervals.

Figure 3: *Petronius tower section under construction (left) and with topsides installed*

Table 3: *Key data of Petronius compliant structure*

Description	Value	unit
Water depth	535	m
Topsides	7,500	ton
Structure weight	43,000	ton

2.2.5 Benguela/Belize

In 2005 the Benguela/Belize compliant piled tower was installed for Chevron off the Coast of Angola. With a topside weight of over 40000 tons and standing in water 390 m deep, the compliant piled tower was considered the cheapest support structure solution.

The structure includes a base template used to fix the position of the foundation piles and to ensure verticality by means of hydraulic jacks, an important issue given the large height to base width ratio. On top of the base template the tower structure was installed in two pieces. Figure 4 shows the tower section during launch and the structure in place with topsides installed. The structure consists of a slender space frame 33 m wide. It is supported by 12 flex piles. The Flex piles are connected to the space frame at a point 120 m below the sea surface. To ensure sufficient flexibility the piles are not restricted in their axial motion. This is achieved by running the piles through a series of guides, providing lateral support of the piles.

Figure 4: *Benguela/Belize tower section during launch (left) and with topsides installed*

Table 4: *Key data of Benguela Belize compliant structure*

Description	Value	unit
Water depth	390	m
Topsides	35,000	ton
Weight of levelling pile template and piles	1,600	ton
Weight of tower base template and foundation piles	15,000	ton
Tower base section weight	24,700	ton
Tower top section weight	8,000	ton

2.2.6 Tombua Landana

The latest compliant tower to be installed is the support structure of the Tombua Landana field. This structure of the Compliant Piled tower type is situated off the coast of Angola in approximately 370 m water depth. It was installed in several phases in the course of 2008. Figure 5 shows the semi-submersible crane vessel Thialf during the installation of the tower bottom section. Also shown in Figure 5 are the foundation piles. Measuring up to 190 m, these piles are the longest installed to this date.

Figure 5: *Installation of the Tombua Landana compliant tower (left) and foundation piles [11]*

The entire foundation comprises a 500 t levelling pile template, four levelling piles of 315 t each, a 3,000 t Tower Base Template and twelve foundation piles, each weighing 850 t. In phase 2 the 30,000 t tower bottom section, the tower top section, the module support frame and three platform modules were installed. Table 5 gives a brief overview of the Tombua Landana Compliant Piled Tower.

Table 5: *Key data of Tombua Landana compliant structure*

Description	Value	unit
Water depth	366	m
Topsides weight	30,000	ton
Tower bottom section weight	30,000	ton
Tower top section weight	6,700	ton

3. Theory of compliant structures

3.1 Dynamics of a single degree of freedom system

Figure 6 (a) shows a single degree of freedom mass-spring-damper system. In Figure 6 (b) its response to harmonic loading is given. In the low frequency range the mass responds quasi-statically. With increasing frequency, the system starts behaving dynamically. When the load frequency approaches the natural frequency of the system, resonance occurs. Beyond the natural frequency the phase difference between the load and the response of the system becomes opposed and the magnitude of the response displacements decreases. Eventually, the displacements become smaller than the quasi-static displacements. The three different frequency ranges described here are the stiffness controlled zone, the damping controlled zone (as the level of damping present in the system determines the height of the resonance peak) and the inertia controlled zone respectively, as illustrated in Figure 6 (b). By dividing the dynamic response by the static response for each frequency, the dynamic amplification factor (DAF) is obtained.

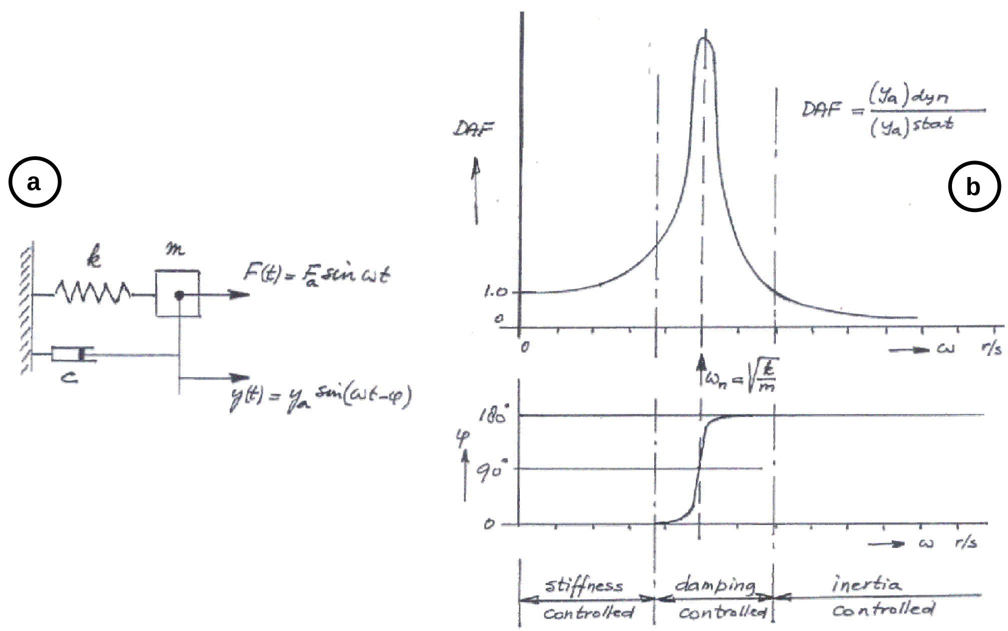

Figure 6: *Dynamics of a single degree of freedom mass-spring-damper system [5]*

3.2 Response to wave loads on offshore structures

The previous section shows how a single degree of freedom system behaves when it is excited by a harmonic load. While simplified, this behaviour is representative for most offshore structures. However, as an offshore structure can be considered to be made up of many elements it will in reality have an unlimited number of natural frequencies. Most of these are in the high frequency range, well outside the wave excitation range. Therefore considering only the first few mode shapes and frequencies will be acceptable in order to describe the structure's dynamic response.

In the offshore environment the waves will usually not be regular harmonic. Instead the sea surface elevation may be described as the result of many different superimposed harmonic waves, each with their own frequency, wave height and direction. If the wave components are assumed to be coming mainly from a single direction, the sea state can be described by a single wave spectrum. This wave spectrum shows the relation between the wave amplitudes and the wave frequencies, in essence showing the distribution of wave energy over the frequencies.

For each of the considered modes the structure's response to every single frequency present in the wave spectrum can be determined, thus obtaining the wave response spectrum. This is shown schematically in Figure 7. The response spectrum shows a peak at the wave spectrum peak and at the natural frequency of the structure.

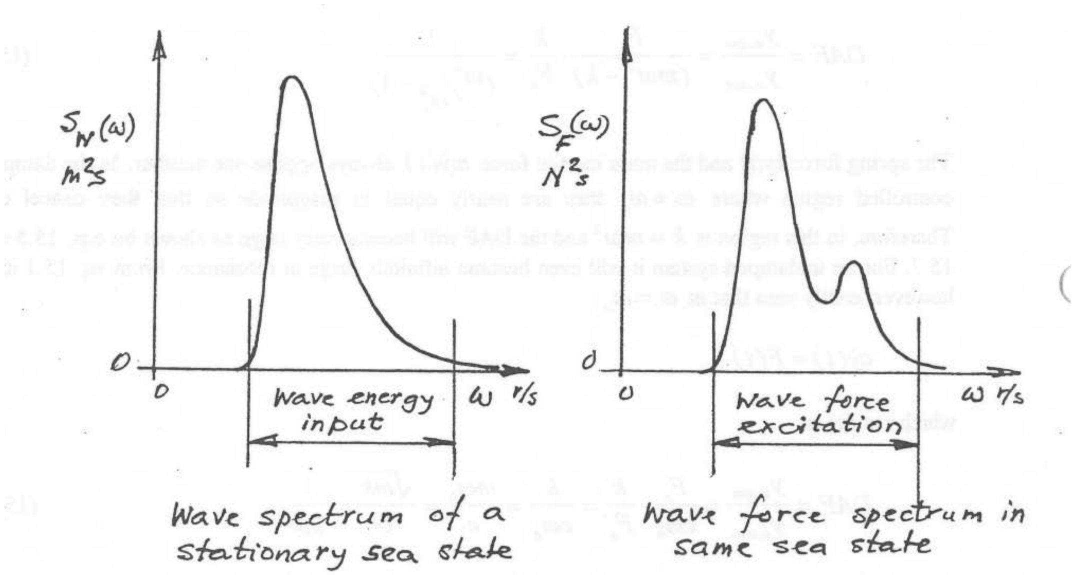

Figure 7: *Schematic model of response at sea [5]*

The magnitude of the response peak at the natural frequency depends both on the structure's dynamic response at the natural frequency as given by the DAF and the magnitude of the energy present in the waves at frequencies around the natural frequency. This is illustrated in more detail in Figure 8. Structure 1 has a natural frequency of approximately 0.33 Hz. This is well above wave frequencies with appreciable wave energy. Consequently the response at its natural frequency is small. However, the quasi-static response at lower frequencies is significant. For decreasing natural frequency it can be seen that the response for frequencies larger than the natural frequency decreases as this is in the inertia dominated range, but the resonance peak increases due to the increased energy content at that frequency. Structure 5 has a frequency below the frequencies with any significant energy content. It can clearly be seen that the resonance peak is relatively low and there is no longer any quasi static response as there is no energy content in the wave spectrum for those frequencies.

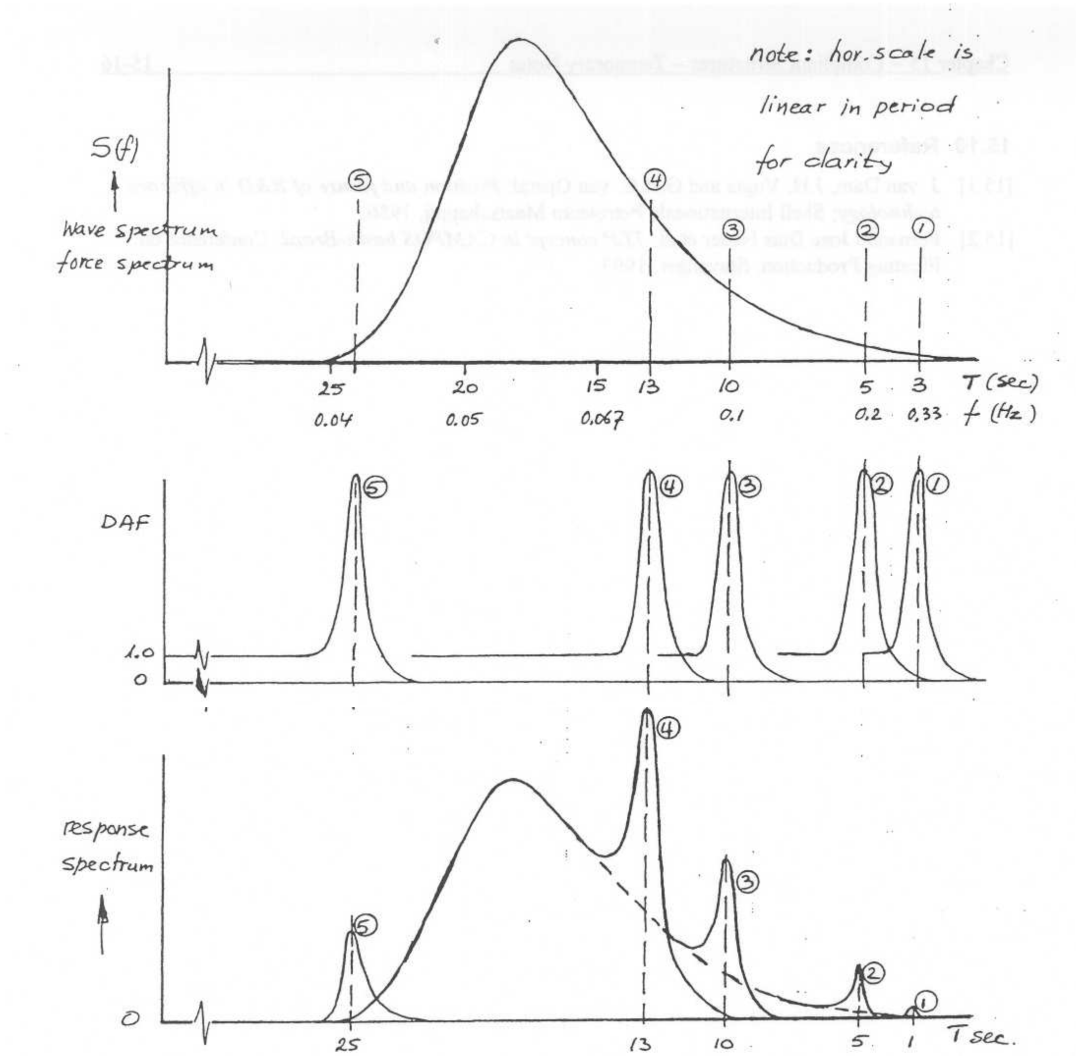

Figure 8: *Response for structures with different natural frequencies [5]*

3.3 Design of fixed offshore structures

For fixed offshore platforms the general approach is to design the structure such that the fundamental natural frequency is higher than the wave frequencies with high energy content in order to avoid resonance. Resonance can lead to excessive dynamic response under extreme conditions, but also under operational conditions, which in turn leads to a reduced fatigue life.

This approach requires the support structure to be sufficiently stiff. The stiffness requirement can usually be achieved by placing the legs far apart in order to attain a high area moment of inertia and by giving the legs sufficiently large diameter.

For shallow water this is a practical approach, but for deep water this results in impractical dimensions and excessive material use, which adversely influence the costs, both for fabrication as well as for installation.

3.4 The principle of compliant structures

In Figure 8 it can be seen that the response of a structure is significantly reduced when the fundamental frequency is below the lower boundary of the wave energy spectrum. This principle is adopted for the design of compliant structures, where the first natural frequency is positioned below the lowest wave frequencies with appreciable wave energy. At the same time it should be avoided that the second natural frequency coincides with wave frequencies in the high end of the spectrum. Therefore the structure must also be designed such that the second natural frequency is positioned above the highest frequency with appreciable wave excitation. This principle is illustrated in Figure 9.

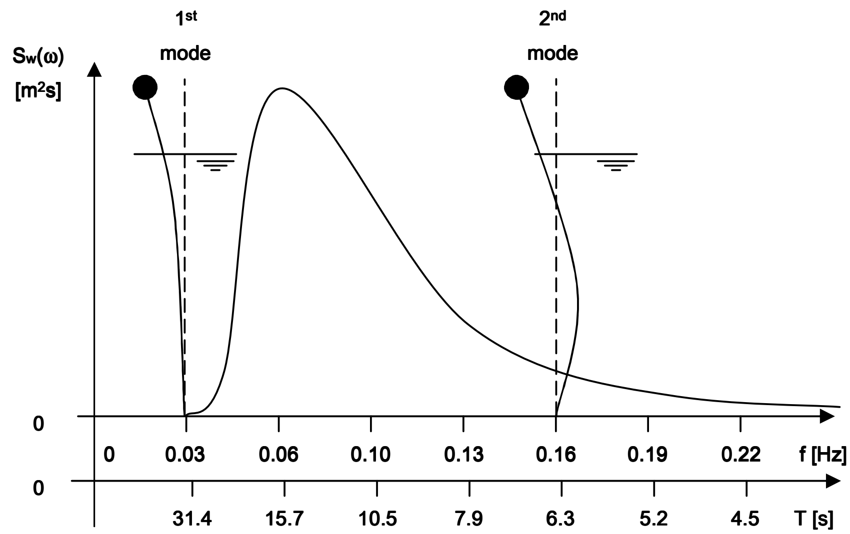

Figure 9: *Principle of compliant structure design*

For the design of the structure this means that the mass and stiffness distribution in the structure should be such that the first natural frequency lies below the lowest frequencies in a severe sea state whereas the second natural frequency lies above the highest frequencies with appreciable excitation in that severe state. Figure 10 shows a simplified model of a compliant tower as used in the offshore oil industry. It shows a large top mass representing the structure's topsides, several concentrated masses representing the distributed mass of the support structure and a rotational and translational spring representing the stiffness of the foundation.

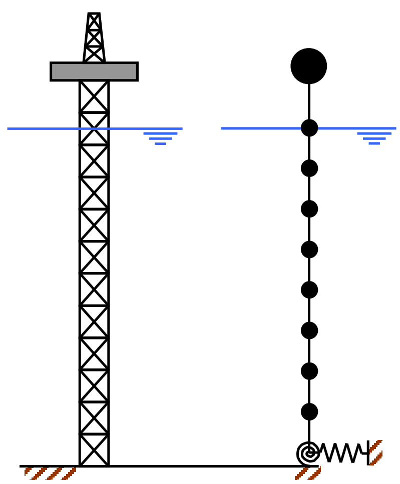

Figure 10: *Simplified model of compliant tower*

The challenge in designing a compliant structure lies in the fact that the first and second natural frequency should be sufficiently far apart and at the same time the structure should be able to withstand (quasi)-static loading from wind, currents and mean wave drift forces. Some form of restoring force will therefore be necessary.

4. Modelling aspects for compliant structures

4.1 Introduction
This chapter describes several aspects that should be considered when modelling a compliant structure. First, general modelling considerations such as influence of water depth and mass modelling are described. Subsequently, the boundary conditions relevant to compliant structures are discussed. Ways of achieving these requirements are also treated.

4.2 General modelling considerations

4.2.1 Water depth
Water depth strongly influences the natural frequency as it determines the length of the structure from seabed to topsides. This length in turn influences the flexibility of the structure. The longer the structure is, the lower its natural frequency.

4.2.2 Mass modelling
The top mass of the structure influences the natural frequencies of the structure strongly. The larger the top mass the lower the natural frequency. The top mass represents any large masses that can be assumed to be concentrated in a local centre of gravity. In the case of an offshore oil platform this could be the deck, accommodation, and processing equipment. In the case of an offshore wind turbine this is usually the rotor nacelle assembly.
The mass of the support structure cannot be assumed to be concentrated in a single point, due to the influence of the position of the mass on the natural frequency. Therefore the support structure is usually modelled as a distributed mass. This in turn can be modelled as a series of concentrated masses at regular intervals. The distributed mass is made up of the mass per unit length of the primary support structure, any marine growth or contained water in flooded members and additional elements that span the length of the support structure such as risers or cables.
Any other elements on the support structure that have large mass can be represented by lump masses.

4.3 Boundary conditions

4.3.1 Foundation
The foundation transfers loads from the support structure to the seabed. The foundation must always be designed such that the vertical loads as well as the base shear can be directed into the soil. In some cases the foundation should be able to transfer bending moments to the soil as well. For certain concepts the foundation should provide the flexibility required to make the structure compliant. Three means of creating a flexible foundation are mentioned in the following sections.

4.3.2 Restoring force
While the compliant tower requires sufficient flexibility for the dynamics, it should also have a restoring force of some sort in order to reduce the deflections of the structure under extreme loading. As these static deflections will usually be largest at the top of the structure, the restoring force should act as high up as possible. The restoring force acts as a spring. With increasing deflection, the restoring force also increases thereby causing the structure to move towards the neutral position. Two main ways of generating a restoring force are discussed in the following.

4.4 Foundation solutions

4.4.1 Hinge
The application of a hinge can be achieved by a true hinge in the form of an articulated joint or by deliberately incorporating soft spots into the structure. The articulated joint has been applied in the past in several offshore structures such as mooring towers and flare towers. Most notably an articulated joint was applied on the North East Frigg platform in the North Sea. The

application of the soft points in the structure was applied on the Baldpate compliant tower. It should be noted that the hinge need not necessarily be located at the seabed.

4.4.2 Piles

Another way of introducing flexibility into the support structure is to design the foundation piles to allow the structure to rotate around the seabed, acting like a pin joint. To obtain this behaviour, the piles should not be spaced too far apart. This approach was applied for the Lena guyed tower where 12 piles were installed in a circle at the centre of the base of the support structure. Unfortunately, placing the piles close to the centre reduces their capacity to transfer torsion loads to the soil. This was solved at the Lena tower by placing a number of torsion piles at the corners of the structure base. These torsion piles should not be allowed to transfer significant loads in axial direction.

A foundation can also be compliant piled. Flex piles are connected to the space frame at a point below the sea surface. To ensure sufficient flexibility the piles are not restricted in their axial motion. This can be achieved by running the piles through a series of guides, providing lateral support of the piles.

4.4.3 Spud can

A spud can is a large diameter conical shell that penetrates slightly into the soil and relies on end bearing to transfer the vertical loads to the soil. This type of foundation is common in jack-up structures. If a single spud can is used, its behaviour will resemble a hinge. However, it is not particularly well suited to transferring lateral loads, which may result in slip.

4.5 Restoring force solutions

4.5.1 Buoyancy

By including a buoyancy tank in the support structure an upward buoyant force is present. When a lateral load causes an excursion of the structure from its neutral position, the structure is under a slight angle with the vertical. The buoyant force can be decomposed in a component parallel to the structure main axis and a component perpendicular to the axis. The perpendicular component causes a moment around the pivoting point of the structure, returning the structure towards the neutral position. Buoyancy tanks are preferably located below the zone of significant wave action to avoid excessive wave loading, yet high enough to generate sufficient restoring force.

4.5.2 Guy wires

The restoring force can also be achieved by using guy wires. Guy wires can either be taut or follow a catenary shape. Taut wires will give the system too high spring stiffness, however, so for compliant structures the catenary configuration must be employed. The catenary wire system obtains its stiffness from the weight of the mooring system. In the neutral position a considerable length of the cable is lying on the seafloor. When the structure moves away from its neutral position a larger part of the cable is suspended and more of its weight contributes to the tension in the cable. The force at the end of the cable can be decomposed into a horizontal contribution and a vertical contribution. The more taut the line becomes, the larger the horizontal component and the larger the restoring force.

Occasionally, clump weights are added to the guy wire system. Under normal operational conditions these will be lying on the seabed, causing the system to behave stiffer. During extreme sea states, when compliant behaviour requires a lower stiffness the forces generated are large enough to pick the clump weight off of the seabed. The additional length of line thus mobilised, the system behaves more compliant.

4.5.3 Structure stiffness

Naturally, the stiffness of the structure itself can also be used to serve as a restoring force. It is however a challenge to accommodate both the dynamic requirements and to keep the displacements in check during extreme loading conditions. A possible way to overcome this is to rely not only on the structural stiffness but additionally on a restoring force such as buoyancy.

5. Compliant support structure concepts

5.1 Classification of compliant structures

The definition mentioned in section 1.2 implies that any structure in the marine environment that reacts to the dynamic forces in a flexible way is a compliant structure. Therefore both floating and fixed structures can be designated compliant structures Compliance can be both in the lateral and in the vertical direction. Bottom mounted compliant offshore structures will always be compliant in the lateral direction only, while floating compliant structures may be compliant in both lateral and vertical directions. Figure 11 shows how compliant structures can be classified into bottom founded support structures and floating structures.

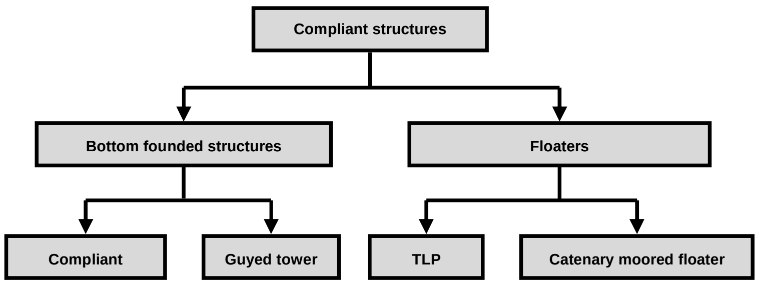

Figure 11: *Classification of compliant structures*

As this document focuses only on bottom mounted compliant structures the floating structures will no longer be considered in this report.

5.2 Concepts in the oil & gas industry

5.2.1 Loads versus resistance

The history of achieved compliant structures in the offshore oil industry was presented in Chapter 2. Among these structures were a guyed tower and several compliant designs relying on different mechanisms to achieve sufficient flexibility. In the previous chapter the boundary conditions were mentioned. These conditions correspond to the type of support or resistance as indicated in the tables in Figure 12. For a guyed tower (GT) and a compliant tower (CT) it is shown which type of support is used to accommodate the static and dynamic loads, both vertically and laterally. Drawing on these examples and on possible combinations of load accommodation a series of concepts applicable to the offshore oil industry are listed and briefly described in the remainder of this section.

TYPE OF SUPPORT/ RESISTANCE	TYPE OF LOAD			
	STATIC		DYNAMIC	
	VERT.	HOR.	VERT.	HOR.
BUOYANCY				
PARTLY BUOYANCY PARTLY SEABED	GT			
SEABED			GT	
CABLES OR SIMILAR CONSTRAINTS		GT		
BALANCED BY INERTIAL FORCES				GT

TYPE OF SUPPORT/ RESISTANCE	TYPE OF LOAD			
	STATIC		DYNAMIC	
	VERT.	HOR.	VERT.	HOR.
BUOYANCY				
PARTLY BUOYANCY PARTLY SEABED	CT			
SEABED		CT	CT	
CABLES OR SIMILAR CONSTRAINTS				
BALANCED BY INERTIAL FORCES				CT

Figure 12: *Conceptual analysis of two compliant structure types [5]*

5.2.2 “Dumb” tower

This concept is called a “dumb” tower, because it does not incorporate any specific features to control its dynamic behaviour. It relies solely on tuning the stiffness of the support structure by adjusting its dimensions to achieve the appropriate fundamental frequency. It also relies only on the support structure to provide a restoring force to accommodate the quasi static loads. If the water depth or the top mass is not sufficiently large, it may be very difficult to attain a sufficiently low fundamental frequency. At the same time the second natural frequency should be high enough. This concept is not likely to fulfil a wide range of different situations. A visual representation of this concept is shown in Figure 13a.

5.2.3 Compliant piled tower

The compliant piled tower, as depicted in Figure 13b, is a modification of the “dumb” tower, where the foundation piles have been designed such to provide the appropriate flexibility for the support structure. The fixation point of the piles to the structure is at an intermediate depth between the sea surface and the seabed, thereby allowing the designer to adequately influence both the first and second mode shapes.

5.2.4 Compliant tower with ‘mass trap’

Instead of adjusting the stiffness, it is also possible to influence the mass of the structure. A mass trap is an efficient way of doing so as the mass acts in the lateral direction, thereby influencing the first and second modes, but it does not need to be supported in the vertical direction. A mass trap can be achieved by enclosing a portion of the support structure, but leaving the top and bottom ends open. This way the contained water mass contributes to the mass of the support structure as a large lump mass, bringing down the natural frequency. Adjusting the size of the mass trap and its position allows the designer to influence the structure’s natural frequencies. The aim is reducing the first natural frequency, while maintaining the second natural frequency. Therefore, the mass trap should preferably be located at the elevation where the second mode goes through its zero deflection point, as mass only contributes where the displacements and hence the accelerations are significant. The compliant tower with mass trap is illustrated in Figure 13c.

5.2.5 Buoyant tower with flex joint

Another way to reduce the stiffness of the structure is to reduce the foundation stiffness. This immediately affects the fundamental natural frequency. One way to achieve this is by applying a flex joint, as shown in Figure 13d. Piles placed near the vertical axis of the structure allow the structure to rotate about the mudline but are well capable of transferring the vertical loads to the soil. To accommodate the quasi static wind and current forces a restoring force is required. In this case the restoring force is accomplished by incorporating a buoyancy tank near the sea surface.

5.2.6 Guyed tower with flex joint

The restoring force in the buoyant tower can be replaced by guy wires, leading to a different concept: the guyed tower with flex joint. (See Figure 13e). The quasi static loads are accommodated by the guy wires. The connection point of the guy wires should be located at the node of the second mode shape.

5.2.7 Articulated column

A relatively common application of compliant structures in the offshore oil and gas industry are compliant offloading structures and flare stacks. These are relatively light structures, where compliance is achieved by means of an articulated joint. Buoyancy serves as a restoring force. The articulated joint can either be a real mechanical hinge or a specifically engineered ‘soft’ spot in the support structure. This type of structure is shown in Figure 13f.

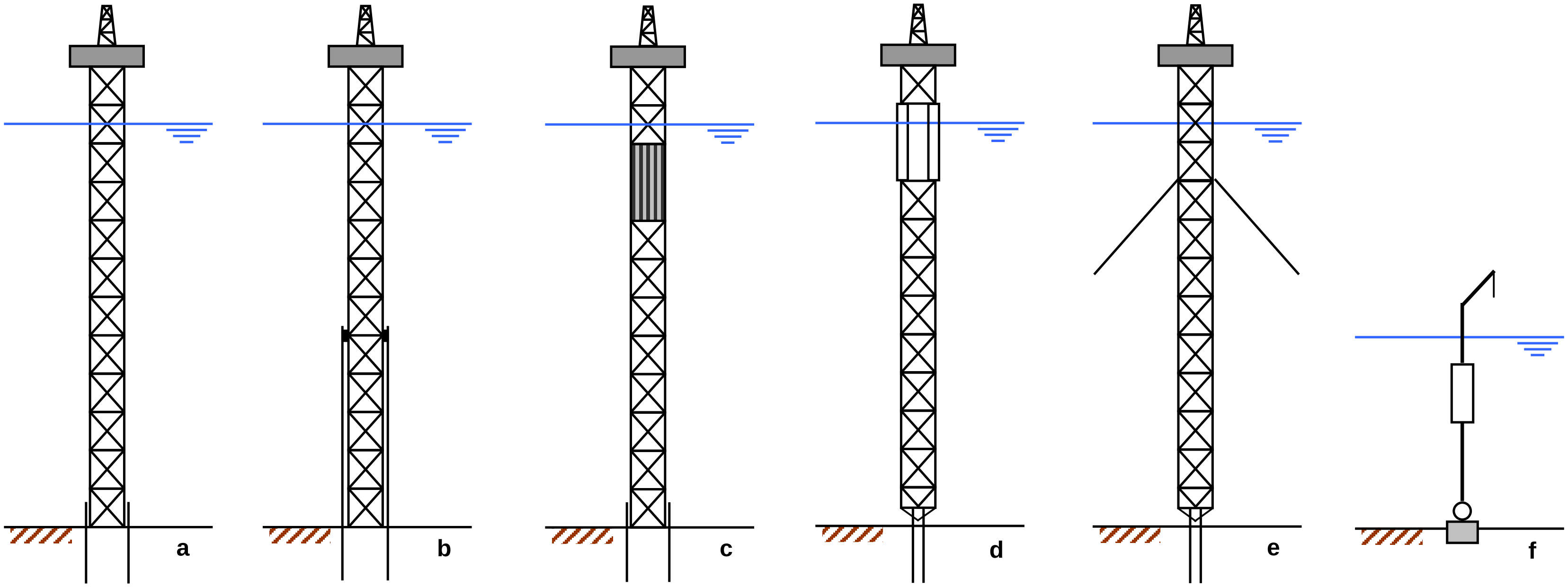

Figure 13: *Compliant tower concepts in the oil and gas industry*

a) “Dumb” tower
b) Compliant piled tower
c) Compliant tower with ‘mass trap’
d) Buoyant tower with flex joint
e) Guyed tower with flex joint
f) Articulated column

5.3 Concepts for offshore wind

5.3.1 Introduction

The same concepts as in Section 5.2 can be envisaged for offshore wind turbines. However, due to differences in boundary conditions, most notably top mass, required (deck) space, water depth, lateral loads and cost efficiency requirements, the eventual shape will be different than the equivalent concepts in the oil and gas industry.

5.3.2 Slender monopile ("dumb tower")

The "dumb" tower could be a simple extension of the monopile concept, where the diameter of the monopile could be reduced to attain the desired fundamental frequency, resulting in a slender monopile. An illustration of this concept can be seen in Figure 14a. However, great care should be taken that the second natural frequency is still in the right range and that the structure does not succumb to buckling due to the large bending moments in combination with the small section modulus. Furthermore, it should be ascertained that the structure has sufficient static resistance to keep top deflections within tolerable limits.

5.3.3 Guyed tower

One way to mitigate the problems mentioned in the previous section is to add a restoring force in the form of guy wires, as illustrated in Figure 14b. While this can alleviate the internal stresses due to quasi static loads, the practical issues associated with guy wires make it a challenge for installation, particularly for offshore wind, where the structures are to be installed in large numbers.

5.3.4 Buoyant tower

Another option for the restoring force is the inclusion of a buoyancy can. This is shown in Figure 14c. Not only does this help to accommodate the quasi static loads, but it also exerts an upward force on the structure, thereby reducing the risk of buckling. Incorporating a buoyant section in the tower may also be beneficial from an installation point of view. It should be noted that to make this option effective, the remainder of the structure should be flooded below the sea surface.

5.3.5 Articulated buoyant tower

While the buoyant tower as indicated in the previous section may be viable for large water depths, it may still suffer from the same problems as the "dumb" tower for shallower sites. To increase the flexibility of the support structure an articulated joint can be included near the seabed. (See Figure 14d) This situation gives the designer sufficient possibilities to tune the structure to achieve the appropriate dynamic and static behaviour.

5.3.6 Tower with mass trap

As for the offshore oil and gas concepts it is also possible for offshore wind turbine structures to influence the natural frequencies by adjusting the mass properties. Including a mass trap may however be more difficult to achieve as the structure should be transparent to avoid vertically supporting the enclosed water mass by the structure itself. A truss type structure is one way to achieve this. (See Figure 14e)

5.3.7 Compliant piled tower

Finally, the compliant piled tower concept may be adopted to ensure compliant behaviour. However, as this structure relies on several piles connecting to the structure at certain elevation above the seabed, this can likely only be achieved for a spaceframe structure as depicted in Figure 14f.

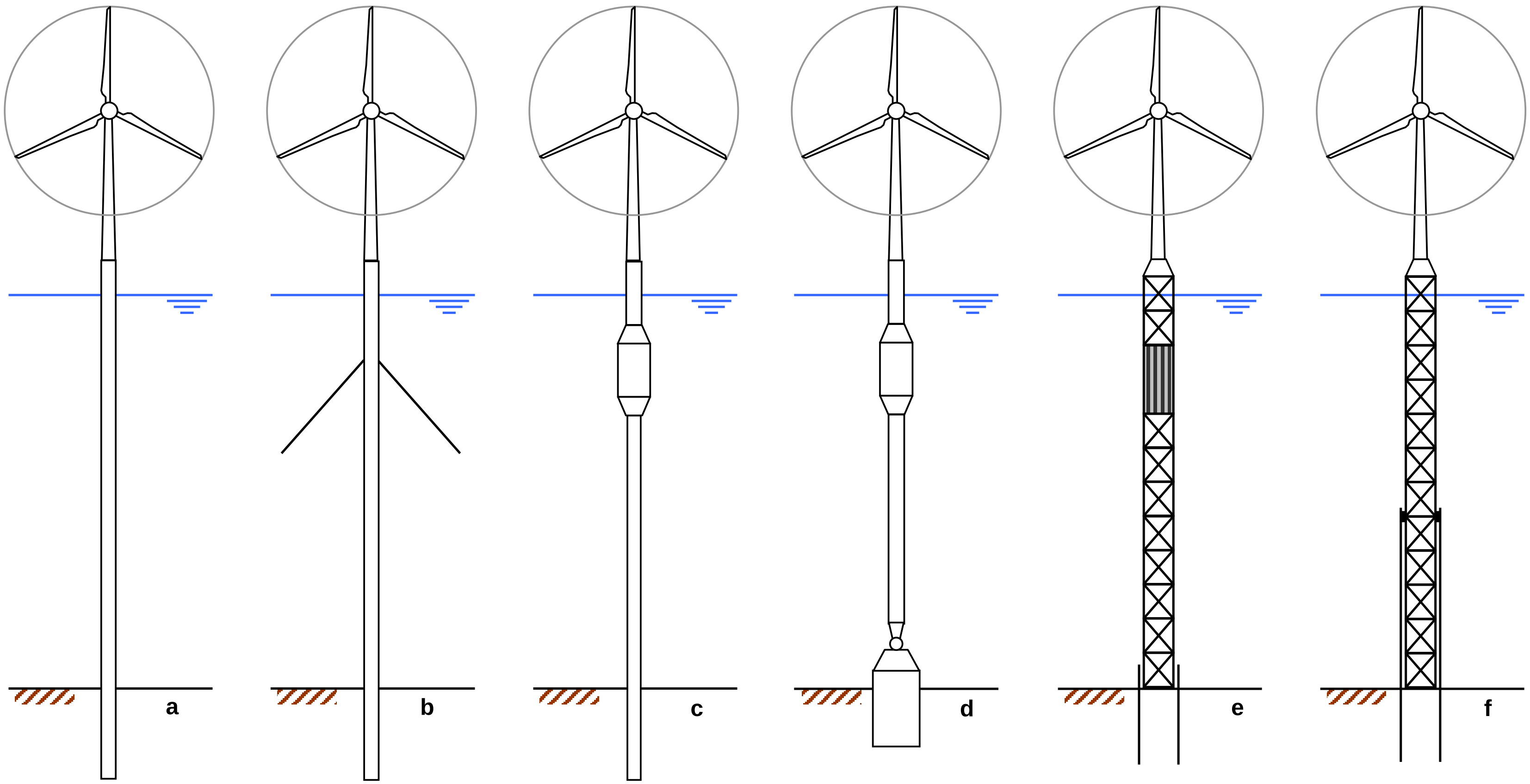

Figure 14: *Compliant tower concepts for the offshore wind industry*

a) Slender monopile (“dumb tower”)
b) Guyed tower
c) Buoyant tower
d) Articulated buoyant tower
e) Tower with mass trap
f) Compliant piled tower

6. Limitations

6.1 Introduction

After generating several concepts, the subsequent step is to evaluate the structure concepts. Although a full evaluation of these concepts is not in the scope of this report, some limitations will be mentioned briefly. These limitations are connected to the validity of load assumptions and to the limitations due to the incorporation of wind turbines

6.2 Validity of wind load assumptions

When dealing with simulating low frequency motions in aero-elastic tools, several limitations should be considered. The first problem is that low frequency motions tend to be large displacement motions that cannot be modelled by the strictly modal-based codes which require small displacements.

The second problem is that low-frequency motions have an aero-elastic influence on the rotor wake that is different than the influence caused by high-frequency motions. This is a problem because many of the aero-elastic models use an implementation that assumes that the time-scales of the turbine motions (vibrations) are much faster than the time-scales of the rotor wake. When modelling a wind turbine on a compliant support structure in such a program, the result of this is that the low-frequency motions will be modelled with less aerodynamic damping than is physical.

The third problem with low-frequency motions is that in nonlinear time-domain analysis it is required to run longer simulations in order to capture a statistically significant number of response cycles. For example, 10 minutes may be a good length for modelling stationary turbulence, but may not be long enough to capture a lot of cycles of very low-frequency motions.

6.3 Limitations for turbines

6.3.1 Closest blade to tower approach

One of the more obvious limitations of the application of wind turbines on compliant support structures is the closest distance of the blades to the tower during operation or in severe sea states during non operational states. Due to the large deflections of the tower the blades may hit the tower. To avoid this, a larger precone or tilt can be applied or the turbine may have a downwind configuration. The latter option may introduce more challenges than it is meant to solve, however.

6.3.2 Other excitation sources

In the previous it is indicated that the natural frequencies should not coincide with excitation frequencies. The focus was mainly on the wave frequency ranges with high energy content. Other excitation sources should also be considered.

Wind excitation has the highest energy content at low frequencies, leading to large quasi static response. Although the number of cycles in this range is relatively low and may therefore not significantly contribute to fatigue damage to the structure, it should be verified that no resonance occurs. In any case the quasi static excitation can be significant and must be counteracted by some restoring force.

Secondly, most turbines operate at variable speed, thereby generating excitations corresponding to the rotational frequency of the rotor. This creates a frequency interval corresponding to the rotational frequency range (1P) in which the natural frequency may not be situated. Furthermore, each time a blade passes the tower an additional excitation is experienced, giving rise to an additional ‘forbidden” frequency interval, the so called 3P range. The challenge now lies in the fact that the first natural frequency should be below the low frequency end of the wave spectrum and above the frequencies of the wind spectrum with high energy, while at the same time positioning the second natural frequency above the wave frequencies with appreciable wave energy, but avoiding the 1P and 3P frequency ranges. Furthermore it should be verified that further rotational frequency multiples do not coincide with higher modes.

6.3.3 Control adaptation

Controllers of wind turbines currently in the market are tuned to operation in the soft-stiff range. Adapting the control to operate in the soft-soft range is possible, but considering the low frequency motions associated with compliant structures, a significantly different approach is required. Lessons can be learnt from studies on floating structures, where large low frequency motions are also present

6.3.4 Position of turbine

The turbine is always located at a relatively large elevation above the sea level due to the fact that the entrance to the tower is at a sufficiently high location above the wave and that the tip of the blade in its lowest position should be a safe distance above that level. Therefore both the top mass and the thrust force on the rotor are at a large elevation above the sea level, resulting in a large overturning moment, without an effective form of restoring force.

7. Discussion and outlook

7.1 Feasibility of compliant offshore wind turbine support structures

Considering the principles of compliant towers, the boundary conditions and the limitations presented in this report it appears that applying compliant towers for offshore wind turbines will be challenging. The offshore industry has paved the way in terms of concepts, several of which can be adapted to suit the needs for offshore wind turbines. However, it appears unlikely to apply compliant towers in shallow water.

Some of the concepts suggested in this report, most notably the articulated buoyant tower show considerable similarities with floating structures, in particular with so called Tension Leg Platforms. Further research should take note of the work done in the field of floating offshore wind turbines. For the moment the feasibility of compliant structures can not be confirmed or denied, although compliant structures could possibly be attractive when hybrid solutions of floating and bottom mounted structures are applied. These could be effective in intermediate water depths, where bottom mounted structures may no longer be viable and floating structures might still need too much buoyancy to be cost effective.

7.2 Avenues for further research

Several suggestions for further research can be distilled from the work presented in this report. First of all an evaluation of the mentioned concepts in terms of actual response under realistic operational conditions should be performed to determine the suitability of the proposed concepts.

Secondly, the impact of resonance of higher order modes with rotor frequency multiples should be determined and ways of avoiding this should be investigated. Also the response due to non-linear mean wave drift forces and low frequency wind excitation should be established.

Subsequently full time domain analysis of the behaviour of most promising compliant structure concepts, including (non-linear) boundary conditions should be performed.

Based on these considerations an assessment can be done and the more promising concepts can be selected for optimisation. Only then could a preliminary cost comparison be done to ascertain the attractiveness of the compliant structure with respect to bottom mounted or floating concepts.

References

[1] **Clauss GF** (2006) *The Conquest of the Inner Space – Challenges and Innovations in Offshore Technology* 21st National Congress on Maritime Transportation, Ship Construction and Offshore Engineering

[2] **Pratt JA et al.** (1997) *Offshore pioneers: Brown & Root and the history of oil and gas* Gulf Publishing Company ISBN 0-88415-138-7

[3] **Gerwick BC** (2007) *Construction of marine and offshore structures* CRC Press ISBN 978-0-8493-3052-0

[4] **McNeilly CC, Will SA** (2006) *Engineering the Benguela-Belize compliant piled tower: fast-track project completes detail design to installation of a bottom-founded production hub in under 26 months* World Oil September 2006

[5] **Vugts JH** (2002) *Handbook of bottom founded offshore structures* Delft University of Technology

[6] **Jonkman J** (2006) *NREL Offshore Baseline 5 MW Manuscript* NREL/NWTC

[7] **van der Tempel J** (2006) *Design of Support Structures for Offshore Wind Turbines* Delft University of Technology

[8] http://www.offshore-technology.com/projects accessed March 27th 2009

[9] http://www.hess.com/ep/us.htm#deepwater accessed March 27th 2009

[10] http://www.doris-engineering.com/horizon/images/photos/baldpate.jpg accessed May 8th 2009

[11] http://hmc.heerema.com accessed July 3rd 2009