THE CONQUEST OF THE INNER SPACE – DESIGN AND ANALYSIS OF OFFSHORE STRUCTURES

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ABSTRACT
Spectacular missions to the moon, the Mars and to other planets of our solar system has boosted public attention to the outer space for the last five decades. During the same period mankind has also conquered the inner space – with fantastic innovations and fabulous inventions – however, hidden under the sea surface, and hence widely unnoticed. While searching for new promising oil and gas fields the offshore industry operates in water depths that have never been explored before. Production systems already reach down to 2000 m, and will probably conquer greater water depths during the next years. Extreme environmental conditions in addition to these enormous water depths call for special solutions. This paper deals with recent developments of offshore deepwater production technology, e.g. SPARs, TLPs, Compliant Towers and huge mono-buoys. After a short survey of the development in ocean engineering from the first shallow water platforms in the Gulf of Mexico in 1947 to today’s deepwater production systems off the Brazilian coast the paper summarizes the principles of platform dynamics in waves to illustrate the advantages of specific design characteristics.

WONDERS OF THE WORLD
In his book ‘De mundi miraculi’ the greek philosopher Philon of Byzanz at about 200 B.C. describes the Seven Wonders of the ancient world, i.e. the Great Pyramid of Giza, the Hanging Gardens of Babylon, the Temple of Artemis at Ephesus, the Mausoleum of Maussollos at Halicarnassus, the Statue of Zeus at Olympia … and two “offshore” structures, the Lighthouse of Alexandria and the Colossus of Rhodes, a huge representation of the sun god Helios which was built astride the harbour at Rhodes.

DESIGN OF OFFSHORE STRUCTURES
Today, more than two millennia later, we admire the Maritime Wonders of the offshore World which are of equal rank as compared to the “miraculi”. The most important parameters in the design of offshore structures are the size of the deposit, the depth of water, and the environmental conditions. Fig. 1 shows schematically the flow of development processes together with design aspects of analysis and evaluation. The decision to open up a field depends on its size, extent, and depth. Production capacity and expected life-span depend on recoverable reserves. Economic criteria combined with environmental conditions and geotechnical data affect system selection and main dimensions, while, in individual cases, construction, transit, installation, operation, and dismantling are also significant. As the deck with its superstructure and equipment is essentially defined by the production process, the hydromechanical and structural analysis and evaluation is primarily aimed at the design and optimization of the bearing structure and its anchorage to the sea bed. Dimensioning depends largely on permanent and operational loadings. Tighter specifications will result from extreme environmental conditions and large hydrodynamic loadings in the seaway.

FIXED PLATFORMS, GUYED AND COMPLIANT TOWERS
Three of the most fascinating offshore structures are presented in the following (Figs. 2-4).

• The North Sea Concrete Gravity Base Structure (GBS) Gullfaks C with a total height of 380 m, a deadweight of 750 000 tons, and a crude oil storage capacity of 2 million barrels (320 000 m³) had a weight of 1.5 million tons during tow-out - equivalent to one
Fig. 1 DESIGN FLOWCHART FOR OFFSHORE STRUCTURES (CLAUSS ET AL., 1992)
third of the mass of the Great Pyramid of Khufu (or Cheops). Hence she is the heaviest object ever moved by man. Fig. 3 illustrates the platform as well as details of construction and installation. Erected in 217-m waters the horizontal force and the overturning moment reach peak values of 712 MN and 65.440 MNm, respectively, requiring concrete skirts at the foundation with a penetrating depth of 22 m.

- Towering 472 m the GBS platform TROLL is substantially taller, requiring concrete skirts which penetrate even deeper into the sea floor to 36 m (Fig. 3). Installed in 305-m waters she produces 80 million m³ natural gas per day – about 1.3 trillion cubic meters during its 50-years operation off Norway.

- With a total height of 492 m the Bullwinkle platform in the Gulf of Mexico in 412-m waters is the world highest rigid steel platform, rising even above the Sears Tower in Chicago by 50 m (Fig. 2). The 45 000 t jacket-type structure has twelve main legs and is anchored in place by 28 single-piece battered skirt piles penetrating 120 m into the sea bed to counteract the 31 300 MNm overturning moment associated with a lateral force of 82 MN. Two central legs, 42 m apart, run parallel and act as cradle runners for launching the platform from a 260-m long and 63-m wide launch barge.

The analysis of the dynamics of large offshore structures reveals that fixed platforms can be designed up to water depths of 450 m in moderate environments. At this depth the resonance phenomena with natural periods in the range of 5-6 s and the associated fatigue problems can still be controlled. At greater water depths these problems become insurmountable for fixed platforms as the energy-intensive part of the sea spectrum at higher resonance periods would damage the structure. To jump across the energy peak of the spectrum, the resonance period

$$T_R = 2\pi \sqrt{\frac{m}{c}}$$

must be substantially increased to a period range of 25-100 s by transforming the wide massive and stiff fixed structure into a flexible, slender tower which is connected to the sea bed either by an articulated joint or by elastic ‘spring’ piles extending to the deck level. This can be achieved by increasing the total mass (or mass moments of inertia – including added mass terms) and a reduction of the restoring forces (or moments).

- The compliant towers BALDPATE and PETRONIUS with heights of 580 m and 610 m in 503-m and 535-m deep waters, respectively, are the highest structures on our planet (Figs. 2 and 4). The design is based on the experience with the prototype, the 27 000 t LENA guyed tower, a 397 m high space-frame jacket,
Fig. 3 GRAVITY-TYPE PLATFORMS GULLFAKS C AND TROLL GAS (CLAUSS, 2000)
installed in 1983 in 305-m waters in the Gulf of Mexico. The slender space frame with constant cross-section dimension of 36 x 36 m² provides enough stiffness to alleviate concern over bending and fatigue. Twelve buoyancy tanks, providing a net buoyancy of 90 MN, are centrally clustered well below the water surface to minimize wave forces. The tower is vertically supported by eight piles grouped in a small circle with a diameter of 17 m near the center of the tower. These main piles, which are conventionally driven to penetration depths of 170 m, are not connected to the tower on the seabed, but extend upwards through ring guides to the pile sleeves at the top of the tower about 17 m above water surface, acting like giant axial springs supporting the compliant tower like crutches. The tower is laterally supported by 20 guylines connected to a heavy truss frame transferring deck loads to the central core of pile sleeves which are welded to the main piles.

An examination of the LENA guyed tower design shows that gravity and environmental loads are reacted by four major resisting elements: pile elasticity, guyline weight, buoyancy, and inertia. Deck loads are carried through the structure to the piles and supported by buoyancy. Lateral stability is provided by extended axial ‘spring’ piles, by buoyancy, and by guylines. The inertia of the tower, including its hydrodynamic ‘added mass’ component, increases its sway period and, consequently, reduces tower motions as well as dynamic loads on guylines and piles.

A critical review of the highly redundant, complicated and expensive LENA guyed tower design reveals that axial ‘spring’ piles are quite sufficient to stabilize the structure. Consequently, the further developed compliant towers BALDPLATE and PETRONIUS use ‘flexpiles’ which are integrated into the main piles (Fig. 4). Depending on its length and pretension the natural period of the compliant tower is tuned to 33 s – like a string instrument. As a consequence, the structures behave like rigid platforms in short waves whereas in rough seas the towers may gently and imperceptibly follow extreme waves – and no resonance effects are observed.

Wonders of the maritime World – the examples prove quite impressively the brilliant achievements of the offshore technology. A water depth of 500 m, however, may be the limitation of bottom supported structures, but not the boundary of offshore oil and gas activities – and not the limit of the ingenuity of ocean engineers. Fig. 5 illustrates the development of offshore platforms and underwater completions over a period of 60 years – the history of conquering the inner space: The basic concept for oil and gas production in deep water is not just the ship but a variety of different species like semisubmersibles, tension leg platforms, SPAR-buoys and huge mono-buoys.
Fig. 5 OFFSHORE PLATFORMS AND UNDERWATER COMPLETIONS (CLAUSS ET AL., 2004)
In the case of floating platforms the most critical parameters are vertical force and/or heave motion. For hydrodynamic optimization the alternative designs make use of the following key characteristics:

- Wave action decays with increasing draft, i.e. water depth \( d \) related to wave length \( L \). At \( d/L=0.5 \) only 4.3 percent of wave action is observed.

- Hydrodynamic ‘added’ mass is an important design parameter. As it depends on component shape and flow direction the total mass of a structure can be tuned accordingly.

- Restoring forces depend on the water surface area. Thus, heave, roll and pitch resonance frequencies can be selected at values outside the high energy range of the seaway.

- Vertical inertia forces on columns and submerged hulls are phase-shifted by 180 degrees. Thus, at a selected wave length the total vertical inertia force is cancelled (due to drag forces, however, small heave, pitch and roll motions are still observed).

- Spacing of components (e.g. columns) results in phase-shifting of (vertical and horizontal) wave forces. Thus, at certain wave frequencies the platforms are not heaving, surging etc.

As a general rule, floating offshore structures are huge, with deep draft, and a sophisticated geometry as well as a specific arrangement of its components. To illustrate the different design options, Fig. 6 demonstrates the consequences of the above principles on the heave response amplitude operator of a semisubmersible.

- With respect to the spectral characteristics of the design sea state the diameter and number of the columns (fixing the restoring coefficient \( c \)) and the geometry of the lower hulls (defining the total mass including added mass contributions) are selected such that the resonance frequency \( \omega_R \) is well beyond the high energy band of the spectrum.

- At the slightly higher cancelling frequency \( \omega_C \) the opposite pressure forces on the upper surface of the hull (higher dynamic pressure acting on the upper hull surface diminished by the nonwetted (punched-out) column areas) and on the lower surface of the hull (lower dynamic pressure, however, acting on a larger area) are compensating each other, i.e. the inertia force is zero, and only small heave motions due to viscous wave forces are observed.

- At wave lengths \( L=2b_0 \ldots 2b_0/3 \ldots 2b_0/5 \) the vertical forces on the respective sides of the semisubmersible are antiphase, and hence no heave motions (but roll motions) are observed (geometrical cancellation).

- Note that with the increase of wave frequency the wave action at greater draft \( d \) is significantly reduced due to the decay of dynamic pressure with \( \exp(-2\pi d/L)=\exp(-d\omega/g) \). Consequently it is recommended to arrange large volume components well below the water surface, and to reduce the waterline area \( A \) of each column as much as acceptable. For ensuring sufficient static stability the spacing of the columns \( a \) must be large enough (considering the contribution \( Aa^2 \) to the waterplane moment of inertia due to the Steiner rule).

In this context the role of hydrodynamic added mass forces \( a_{33}(\ddot{z}-\dot{w}) \) and of (linearized) viscous forces \( b_{33}(\dot{z}-w) \) are illustrated in more detail: They depend on relative motions between structure and wave, with \( \dot{z} \) and \( \ddot{z} \) being the velocity and acceleration of the structure component in vertical direction, and \( w \) and \( \dot{w} \) the associated (vertical) orbital velocity and acceleration, respectively. With the Froude-Krylov-force, i.e. the force due to the pressure field of the undisturbed wave

\[
F_{FK} = -\int p\eta ds ,
\]

as well as with the inertia force \(-\rho\ddot{z}\) and the restoring force \(-c_{33}\dot{z}\) the equilibrium of vertical forces results in

\[
F_{FK} - \rho\ddot{z} - c_{33}\dot{z} - a_{33}(\ddot{z}-\dot{w}) - b_{33}(\dot{z}-w) = 0
\]

After separation of variables we obtain the motion equation

\[
(\rho\ddot{z} + a_{33})\ddot{z} + b_{33}\dot{z} + c_{33}z = \frac{F_{FK} + a_{33}\dot{w} + b_{33}w}{\text{linearized wave force (based on Motion equation)}}
\]

The left hand side of this equation defines the motion characteristics of the oscillating structure, the right hand side yields the wave exciting force, resulting from the Froude-Krylov-force, the added mass force and the (nonlinear) drag force.
Fig. 6 HYDRODYNAMICS OF OFFSHORE-STRUCTURES – HEAVE MOTION OF SEMISUBMERSIBLE
Thus, the added mass $a_{33}$
- increases the total mass of the structure and shifts the resonance frequency $\omega = \sqrt{c_{33}/(\rho a_{33} + a_{33})}$ to advantageous lower values
- contributes unfavourably to the wave excitation force, if structure components are not deep enough, and thus exposed to wave action.

Similarly, the viscous force coefficient $b_{33}$ defines
- the damping force which limits the vertical motion at the resonance frequency, and
- the wave exciting force resulting in substantial motions at the cancellation frequency (see Fig. 6).

Based on the above design principles a great variety of semisubmersibles (Fig. 7) and Tension Leg Platforms (TLP) (Fig. 8) have been constructed. Low heave motion is the most important design target of semisubmersibles. Operation displacement of exploration and production platforms vary from 15 000 tons to 50 000 tons with typical deck loads between 1000 tons to 7000 tons. In rough seas semisubmersibles can be used as production platforms as shown in Fig. 7 presenting the GVA 5000 (with a displacement of 35 000 tons and a variable deck load of 7150 tons) as core of the floating production system BALMORAL at a water depth of 143 m. Very special semisubmersibles are the four gigantic crane vessels Balder and Hermod as well as Thialf and Saipem 7000 with displacements up to 178 000 tons and a tandem load capacity of 14 000 tons.

With tension leg platforms low vertical force in rough seas is the key design target. To prevent the tendons of falling slack – even in the deepest trough – substantial pretension is required increasing the free floating draft by 9 m to 13 m depending on the design wave. In case of the light-weight TLP Jolliet in the Gulf of Mexico in 535-m waters with a displacement of 4200 tons the draft is increased by 9 m to 24 m. The huge concrete TLP Heidrun with an outstanding displacement of 290 000 tons – operating in the Haltenbanken Field in the Norwegian Sea in a water depth of 350 m – requires a pretension of 30 000 tons which increases the draft by about 11 m to 77.5 m. Resonance periods of 132 s (surge/sway) and 92 s (yaw) as well as 3.1 s (heave) and 3.5 s (pitch/roll), respectively, proof the good motion characteristics of this platform.

**Fig. 7 SEMISUBMERSIBLES (CLAUSS ET AL., 1992)**
Even if hydrodynamic characteristics are decisive for the design of offshore platforms in rough seas also structural features and – last not least – economical criteria must be considered – referring to construction, operation and decommissioning. Variations of requirements or environmental conditions lead – as has been experienced many times in the history of ocean engineering – to completely new concepts which prevail on the market against approved and optimized ‘old’ designs. In simple words: The worst enemy of an excellent design is … the better concept. Such a new development is the SPAR which initiated a completely new family of deep water offshore platforms.

**SPAR PLATFORMS AND MONO-BUOYS**

SPARs are vertical circular cylinders with a draft of about 200 m – large enough to minimize vertical wave forces. An early precursor is the oil storage loading buoy Brent SPAR which – more precisely – is a monocolumn semisubmersible with a deeply submerged cylindrical caisson (Fig. 9). The classical SPAR looks quite simpler: The SPAR production platform NEPTUNE is a 198-m long cylinder with a diameter of 22 m. However, the cross section reveals that it integrates a square bay with 16 slots for self-supporting production risers. The risers – autonomously connected to the subsea template by tapered titanium stress joints – are tensioned by buoyancy can guides at the upper end. Thus, the vulnerable production system is protected against wave forces in the center of the gently heaving SPAR platform. As the vertical motions of the SPAR are rather small, surface trees are used connected by flexible flowlines to the production manifold on deck. The classical SPAR consists of an upper buoyancy tank (hard tank), a flooded middle section and a floodable soft tank at the lower end which helps to turn the platform upright from transit to the operational position. The huge cylindrical structure is equipped with a helical strake to avoid harmonic vortex shedding which would excite disastrous lateral oscillations of large amplitude. After the installation of the first SPAR-platform NEPTUNE in 1996 in 588-m waters in the Gulf of Mexico more than 10 structures of this type have been installed in water depths - up to nearly 1800 m (Devils Tower, water depth 1710 m).
Fig. 9 OIL STORAGE BUOY BRENT-SPAR AND THE SPAR-PRODUCTION SYSTEM NEPTUNE

Fig. 10 DIFFERENT TYPES OF SPAR-BUOYS
As illustrated in Fig. 10 the design has been further developed. Especially, with the Truss-SPAR a significant reduction in total weight is achieved by integrating heave plates which increase the added mass of the platform considerably.

Due to the increased added mass (in vertical direction) the heave resonance frequency decreases from $\omega_0 = 0.33$ rad/s to 0.244 rad/s, and the associated heave response from $4.3 \zeta_a$ to $1.7 \zeta_a$, respectively (wave amplitude $\zeta_w$). This results in a maximum heave of 1 m only in a 100-year hurricane. As compared to the classical SPAR the heave plates increase the virtual mass only in the vertical direction whereas the horizontal mass is not affected, and thus lateral forces are significantly smaller. In addition, heave plates with its high drag forces are damping vertical motions considerably. In conclusion, Truss-SPARs are smaller as compared to classic SPARs, with

- better damping characteristics
- smaller surge motions due to the transparency of the structure
- smaller vortex-induced oscillations
- about 20-40% lower production cost
- simpler and faster production
- simpler transport as one-piece and
- easier inspection.

As the SPAR-concept turns out to be a very promising principle also multicolumn variants like the TRUSS-SPAR-EDP – an extendable platform – have been proposed (Fig. 13) (Maksond, 2004).

Another variant of the SPAR-concept is the SSP – the Sevan Stabilized Platform. In this case the diameter of the circular cylinder is substantially larger – 60 m for smaller units, 106 m for the biggest buoy. At moderate drafts between 17 m and 33 m, respectively, the huge buoys reach displacements from 55 000 tons (SSP 300) to 305 000 tons (SSP 2000), providing a storage capacity between 0.3 Mio bbl and 2 Mio bbl (Sevan Marine, 2006). The first unit, the SSP 300 –
Piranema (see Fig. 14 and Fig. 15) (so called for its 300 000 bbl oil storage capacity) – with a processing capacity of 30 000 b/d oil and 3.6 million m³/d gas – will be installed in Brazilian waters in some 1000 m using a 3 x 3 hybrid mooring system for connection to 21 risers and umbilicals (Wertheim and Abrantes, 2006). Due to the immense size the pressure field on the lower surface of the cylinder shows saddle-type distributions, with the consequence, that the oscillating vertical forces, and hence the heave motions remain small.

CONCLUSIONS
In this paper the conquest of the inner space has been demonstrated by fascinating developments in offshore technology. With deeper oil and gas fields, increasing distances from the coast and rougher sea states ocean engineers face new challenges – and respond with innovations. As compared to terrestrial structures the design of offshore structures has some special features:

- Horizontal forces are in general some ten times greater than in land-based structures, and produce extreme bending and overturning moments as the wave forces act near the water surface.
- Dimensioning depends critically upon sea conditions, and the design may be dominated either by peak loading or by fatigue strength aspects.
- The fluid in which the structures exist allows weight forces to be wholly or partly offset through buoyancy. The great buoyancy of water – some 800 times that of air – permits the concept of compliant floating structures which are extremely heavy but which are, nevertheless, anchored to the sea bed rather like a tensioned, inverted pendulum or an aerial balloon.
- Unlike land-based constructions with their associated foundations poured in place, offshore structures are usually constructed at shore-based building sites remote from the deepwater installation area, and without extensive preparation of the foundation. In the case of reinforced-concrete platforms, the foundation is fully integrated, so that they can be towed to the site and lowered without further preparation. With steel platforms - after tow out upending, and set-down - a deep-pile foundation is driven, which involves the use of powerful pile-driving equipment and can only be carried out during short periods of favourable weather. A further peculiarity is that offshore structures, to be built and moved out to the operation site, must be capable of floating, even if they are to end up as fixed platforms.

In general preparation of the foundation area is limited according to environmental conditions. Another major restriction results from the fact that oil and gas are explosive, inflammable materials under high pressure and at temperatures considerably higher than seawater. These factors must be taken into account in addition to the design loadings already discussed including subsidence, creep phenomena, and thermal stresses. Also, the possibility of catastrophic events such as explosions and fires, collisions with ships, or structural failure, all of which could result in total destruction, must be considered.

As shown in Fig. 16 the sea states, in particular the design sea state will govern all decision concerning the concept, the design and the construction-considering transit, installation, operation and dismantling. With increasing water depth jackets reach their limitation as elastic bending modes become uncontrollable. By jumping the energy hump to lower resonance frequencies engineers developed guyed, articulated
and compliant towers. At still greater water depths a range of new concepts have been created, like semisubmersibles, tension leg platforms and specialized ships. Recently upcoming new species like SPARs and the huge mono-buoys indicate that we may expect more Wonders of the Maritime World in the near future.

ACKNOWLEDGMENTS

This paper is based on numerous research projects and teaching experience. Hence, it is unrenounceable to cooperate with a partner for discussion and review. My assistant Dipl.-Ing. Robert Stück has supported me for weeks to arrive at this final version. I appreciate his valuable help and thank him very much.
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