Marine Hydrodynamics with Applications on Ships and Offshore Structures – A Brief Introduction

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Introduction

A brief overview is made to some of the important marine hydrodynamic problems related to maritime transportation and offshore oil and gas exploration. Seakeeping dealing with global motions and loads on ships, maneuvering dealing with the control of ships and resistance & propulsion associated with energy efficiency are the most relevant hydrodynamic topics in the shipping industry. Most of the offshore structures are exposed to the environmental condition without possibility of avoiding the heavy weather as the ships can do. Related hydrodynamics challenges are discussed in relation to offshore structures operating in shallow, intermediate and deep water areas.

Only a few of the important marine hydrodynamic problems are introduced, with many other important hydrodynamics-related topics not touched upon in this article. Examples are deep water marine operations, offshore wind and wave energy devices and sloshing in LNG tanks.

Maritime industry

Within the maritime industry, marine hydrodynamics is traditionally divided into three sub-topics, e.g. seakeeping, maneuvering and resistance & propulsion.

Seakeeping related problems

Seakeeping deals with the motions responses and global wave loads of the ship in waves, which may have a direct consequence on for example capsizing of ships, the structural damage of ship hull and comfortableness of crew on board.

The famous Norwegian Viking ship Saga Siglar which travelled around the world during 1983-1984 capsized outside Barcelona in a storm. Recently seakeeping study based on model tests in Marintek for Saga Siglar showed that this vessel could not survive in waves with maximum wave height 12 meters. Saga Siglar was 16.5 meters long and has a 0.6 meters draft in ballast condition and 1.3 meters draft when loaded with cargo. Figure 1 shows the artist impression of Saga Siglar.

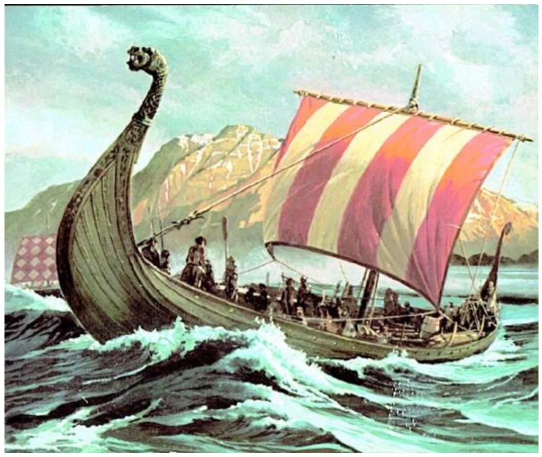

Figure 1 Artist impression of Saga Siglar

Structural dynamic response of the ship when travelling in waves occurs due to the dynamic loading. This phenomenon is referred as springing and whipping in the literature. Springing and whipping introduce significant fatigue damage to the ship hull and contribute to the maximum stress in the ship hull structures. This is of particular interests for larger ships which tend to be more and more flexible from a structural dynamics point of view. The lengths of new-building increase dramatically year by year. The world-largest container ship is 398 meters long and 58 meter in width (based on data until 2013). On 17 June 2013, the Japanese container ship MOL Comfort suffered a crack amidships in bad weather about 200 nautical miles (370 km; 230 mi) off the coast of Yemen and eventually broke into two. See Figure 2. It is believed by researchers that springing and whipping have been part of the important reasons for the failure of the ship structure of MOL Comfort.

Figure 2 Mol Comfort broken in progress

Ship motions also limit the comfortableness of crew and passengers on board. People on board of a ship may feel seasick when the acceleration of the ship exceeds certain values. This occurs for ships travelling in bad weather, accompanied by large amplitude ship motions.

Maneuvering related problems

Maneuvering means that a ship master is operating the ship by turning, course-keeping, accelerating, decelerating or backing the ship. We can make analogy of ship maneuvering to a driver operating the car. One example of maneuvering is replenishment between two ships. Replenishment is a method of transferring fuel, munitions, and stores from one ship to another while under way. Replenishment operation in open sea is considered "the most dangerous naval operation in peacetime". The two ships tend to pull each other together due to the hydrodynamic interaction effects. Similar phenomenon occurs when for vessel moving in ports is due to ship-ship interactions or ship-port structure interactions, the last being, for instance, bank suction effects where banks can also be submerged structures or local water depth changes. As consequence, ship collision or grounding may occur.

Figure 3 Bird view of a craft carrier under replenishment operation

Resistance and propulsion

The power of the installed propulsion machinery on board of the ships should be enough to overcome the possible maximum resistance from the water applied on the ship and maintain the speed at specified speed. In case of insufficient power, the ship may lose its planned speed when travelling in waves leading to delays of cargo delivery. On the other hand, unnecessarily larger propulsion system is costly and not energy efficient. The International Maritime Organisation (IMO) has developed the Energy Efficiency Design Index (EEDI) to measure the level of energy efficiency of a ship. This has been adopted and entered into force from January 1st, 2013 as a mandatory requirement, requiring a minimum energy efficiency level for all the new ships.

The increased awareness from the shipping industry to reduce the environmental impact by aggressively lowering its emissions to air combined with uncertainties in volatile fuel costs, has resulted in the need for highly optimized hull forms and propulsion systems. The ship resistance can be improving the hull efficiency (e.g. optimized streamline hull form design + Trim and draft optimization), propulsion efficiency and the power plant efficiency on board the ship. Taking a fuel saving of 2% for example, the fuel saves for a handy-size bulk carrier is about 80 tonnes with cost saving about 50,000 USD per year. With a fuel saving of 2%, a cape-size bulk carrier saves around 200 tonnes corresponding to approximately 120,000 USD per year.

Offshore oil and gas industry

From hydrodynamic points of view, one of the essential differences between the ships and the offshore structures is that most of the production offshore units are permanently positioned (by for example mooring system or dynamic positioning system; or the combination of both) at the oil field and thus not able to avoid the heavy weather as the ship can do by escaping from the area of the storms. The design of offshore structures and positioning system should be robust enough to survive in extreme environmental conditions.

Looking back to the offshore oil & gas industry, the activities moves gradually from near shore area with shallow water depth to deeper waters. Depending on the water depth, different concepts apply. It has been popular to use the bottom-fixed concepts, e.g. Jacket and Jack-up platforms in the shallow water. For intermediate water depths, both the bottom-fixed platforms and the floating systems (such as FPSOs, semi-submersibles and TLPs) are in use. With even deeper water depths, it is more economical to use floating system. See Figure 4 for different offshore platform concepts in different water areas.

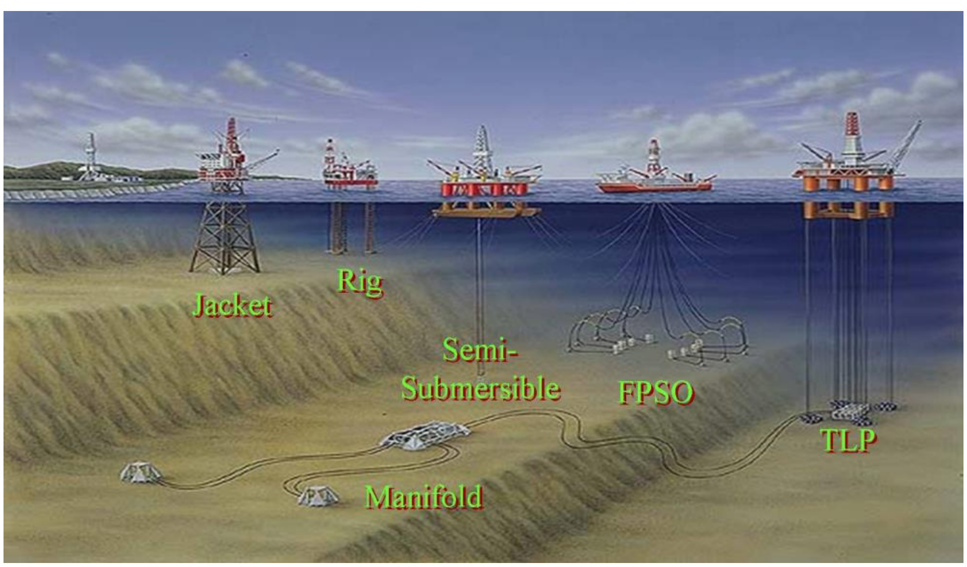

Figure 4 Concepts of offshore structures in shallow-, intermediate- and deep water depth.

Shallow water challenging

Since most of the offshore structures in the shallow water region are fixed to or sitting on the sea floor. The wave induced motions of the structures are not a concern. From hydrodynamics point of view , one of the major challenges for the offshore oil & gas activities in near shore area is the highly nonlinear shallow water waves and the resulting extreme wave loading on the structures, e.g. the bottom-fixed offshore platform. The same challenges apply for the offshore wind industry, where wave impacts introduce significant structural dynamics of the wind turbines.

As a physics process, when the waves from deep wave enter the shallow water region, they slow down, grow taller, change shape and eventually break. See an example of a plugging breaking wave in Figure 5. The velocity of the water on the tip of a breaking wave is very high, which can potentially lead to very large impact forces and damage on the offshore structures. Breaking waves passing through a jacket oil platform is depicted in Figure 6.

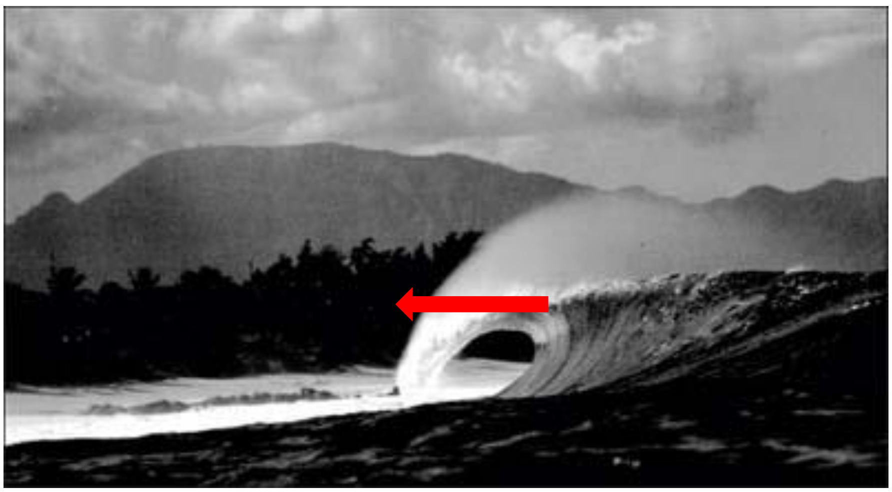

Figure 5 Large horizontal velocity on the tip of a breaking wave.

Figure 6 Breaking wave passing by a jacket platform

Challenges related to offshore floating system

The floating offshore systems are normally positioned by mooring lines, dynamic positioning system or the combination of both. To understand the physics in the simplest way, one may consider offshore floating system as sketched in Figure 7. The offshore floating unit is modeled by a large mass exposed to wind, current and waves. The large mass is connected to seafloor by mooring lines and risers. Due to the soft stiffness of the mooring lines, most of the floating system has large natural period in order of 100 seconds for the horizontal motions. The ocean waves do not have significant energy to directly excite the resonant horizontal motion of the moored offshore structures. However, due to the complex nonlinear evolution the waves themselves and their nonlinear interactions with the floating structures, the resonant motions still occur in reality. Since both the stiffness and damping are small, even a small excitation force can results in large horizontal motions of the floating structures. This motion is often referred as 'slow-drift' motion which is very important in the mooring system design. As a consequence of large 'slow-drift' motions, the mooring lines suffer large dynamic loading which potentially lead to damage of mooring system.

Mooring system failure incidents with line breakage have been experienced on several rigs and FPSO's in the Norwegian and UK offshore sectors during recent years. Most of them are related to moderate-to-heavy sea states, typically estimated to correspond to around 1-year storms. A direct cause is believed to be overload from extreme and steep waves or wave groups that could lead to larger slowly varying wave forces and larger resulting offsets than was expected from use of standard prediction tools.

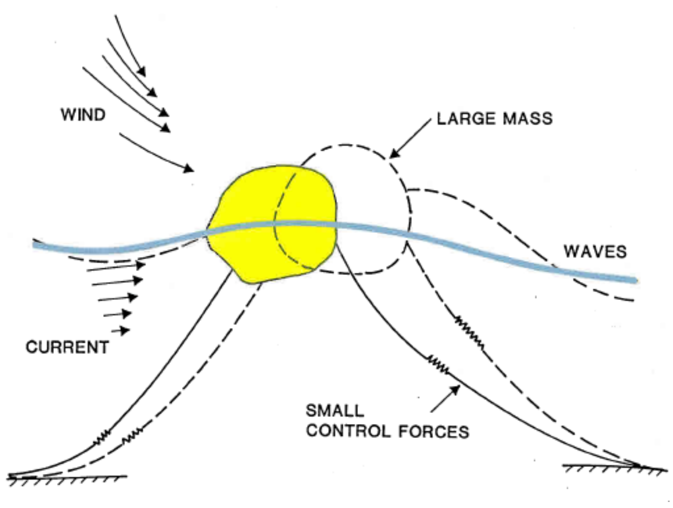

Figure 7 Simplified model for offshore floating system connected to seafloor with mooring lines/risers while exposed to environmental condition including wind, current and waves.

In principal, the mooring system and the floating system (modeled as large mass) are fully coupled. When the weights of the mooring lines and risers are much smaller relative to the 'large mass' alone, the system can be de-coupled. However, for deep water facilities, the mooring system and risers are heavier which makes the coupling effects more and more important.

New challenges in deep and ultra-deep water challenges

Oil and gas production moves into increasingly deeper water towards 3000m depth. The fact that about 80% of oceans are deeper than 3km opens for challenging explorations, mappings and industrial developments in a long-term perspective. The floating offshore structures are easily exposed to harsh environmental conditions when they are far away from the shore. One example is the Freak waves characterized by an unusual large ratio between maximum wave height and significant wave height were measured at Draupner.

Current and internal waves are of more concern than free-surface waves for ultra-deep structures. Internal waves are gravity waves that oscillate within, rather than on the surface of, a fluid medium. To exist, the fluid must be stratified meaning that the density decreases continuously or discontinuously with height due to changes. Internal waves were governing in the design of APL loading buoy at Lufeng, South China Sea. Since the characteristic time of the considered internal waves are 20 minutes, they act as a steady current with strong variations over a depth of about 300m. The maximum horizontal velocity is around 3m/s in a 100-year return period.

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