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Very Large Floating Structures: Applications, Research and Development

C.M. Wang[a], Z.Y. Tay[a]

[a] *Department of Civil Engineering, National University of Singapore*
Kent Ridge, Singapore 119260

Abstract

Very large floating structures (VLFS) have attracted the attention of architects, city planners, and engineers because they provide an exciting and environmentally friendly solution for land creation from the sea as opposed to the traditional land reclamation method. The applications of VLFS as floating piers, floating hotels, floating fuel storage facilities, floating stadia, floating bridges, floating airports, and even floating cities have triggered extensive research studies in the past two decades. The VLFS technology has developed considerably and there are many innovative methods proposed to minimize the hydroelastic motion, improve the mooring system and structural integrity of the VLFS. This keynote paper summarizes the applications, research and development of VLFS over the past two decades.

Keywords: Very large floating structures; Hydroelastic response; Mooring system; Structural integrity;Anti-motion devices

1. Introduction

Very Large Floating Structures (VLFS) are artificially man-made floating land parcels on the sea. They appear like giant plates resting on the sea surface. VLFS may be broadly categorized into the semisubmersible-type and the pontoon-type. The semisubmersible-type VLFS has a raised platform above sea level by using column tubes and is suitable for deployment in high seas with large waves. In contrast, the pontoon-type VLFS platform rests on the water surface and is intended for deployment in calm waters such as in a cove, a lagoon or a harbor.

The concept of VLFS was first introduced in circa 1920 when Edward Armstrong proposed a seadrome as stepping stones for aircrafts flying across the oceans. However, the enthusiasm for building these floating airfields was dampened by the extraordinary non-stop flight of Charles Lindbergh from New York to Paris in 1927. In the Second World War, the US Navy Civil Engineering Corps used this floating airfield concept to construct a floating pontoon flight deck measuring 552m x 83m x 1.5m with a draft of

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0.5m for use by Great Britain (Laycock 1943). The US navy also proposed mobile offshore bases (MOB) as early as in the pre-cold war era to support military operations where conventional land bases were not available (Suzuki *et al*. 2006). It was not until the 1970s that the VLFS technology was revived and developed further by the Japanese to create a floating airport for the Kansai International Airport and a floating city such as the Okinawa International Ocean Exhibition - Aquapolis. Although the Kansai airport did not adopt the floating airport design, the research and development exercise prepared the Japanese engineers and naval architects to build the Mega-Float in Tokyo Bay in 1995 as a test floating runway. The Mega Float provides an excellent life size structure for understanding the hydroelastic behavior of VLFS, the mooring systems, the connector system, the anticorrosion system and its effect on seawaves, currents, water quality and marine eco-system. Through the Mega Float research programme, engineers are able to validate their hydroelasticity codes, the performance of the rubber-fender-dolphin mooring system, the performance of welded connections and the effect of wave action on VLFS as a floating airfield. Also, the following advantages of VLFS over the traditional land reclamation solution are discovered: VLFSs are environmentally friendly as they do not damage the marine eco-system, or silt-up deep harbors or disrupt the ocean currents; they are easy and fast to construct; they can be easily removed or expanded; and they are not affected by seismic shocks since they are inherently base isolated (Wang *et al.* 2008).

In this paper, we will focus on the applications, research and developments of the pontoon-type VLFS for sea space utilizations over the past two decades.

2. Applications of VLFS

From 1995 to 2001, the Japanese constructed and studied the performance of the Mega-Float (a 1 km long floating test runway in Tokyo bay, see Figure 1) in order to develop and to investigate the soundness of the VLFS technology for use as a floating airport. The conclusion of the study is that VLFS is indeed feasible for floating airports, even with the stringent requirement that the radius of curvature of the runway be kept at 30,000 m. Some other applications of VLFS in Japan are the floating fuel storage bases at the Shirashima island and Kamigoto island (see Figure 2), and floating ferry piers at Ujina port, Hiroshima.

VLFS also finds application as floating bridges. They are economical solutions when the water depth is large or the riverbed/seabed is very soft. A well known very large floating bridge is the 2013m long Lacey V. Murrow Bridge and the Third Washington Bridge over Lake Washington in Seattle. A more recent floating bridge is the one over the Dubai Creek and it is 300m long.

Singapore has built the world's largest floating performance stage at the Marina Bay (see Figure 3) and is planning to construct a mega floating fuel storage facility (FFSF, see Figure 4) off Pulau Sebarok to cater for the increasing demand for oil storage capacity. Such FFSF may double up as bunker cum mooring system for ships, thereby relieving traffic congestions in the Singapore harbour and decreasing the turnaround time for ships.

South Korea has also initiated a number of VLFS projects. Construction is underway to build three floating islands (named as Viva, Vista and Terra) on the Han River for entertainment and convention centres (see Figure 5). The VLFS team of the Samsung Heavy Industries is working on a floating cruise terminal for Seoul (Figure 6) which also houses hotel rooms and CIQ (customs, immigration and quarantine), and a floating mobile quay system.

Figure 1: Mega-Float, Tokyo Bay

Figure 2: Floating oil storage base at Kamigoto Island

Figure 3: Floating performance stage @ Marina Bay, Singapore

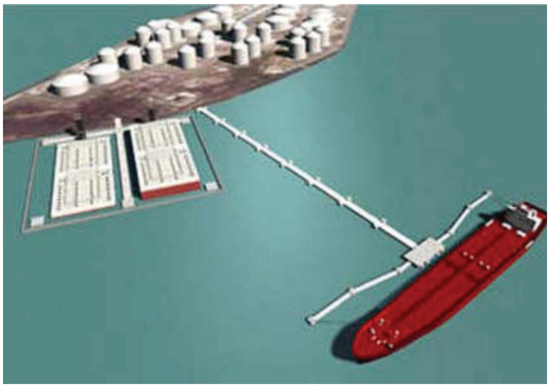

Figure 4: Proposed floating fuel storage facility (Photo courtesy of JCPL)

Figure 5: Floating island on Han River

Figure 6: Proposed floating cruise terminal for Seoul (Photo courtesy of Dr S.W. Na, Samsung Heavy Industries)

The application of VLFS as floating farms in urban cities may also emerge as an innovative solution to provide arable land in supplying food to the increasing growth of human population while maintaining the integrity of the ecosystem. The sustainable engineering science barge (Figure 7) is constructed by the New York Sun Works Center on the Hudson River in Manhattan to demonstrate that urban agriculture on floating structure is possible without causing damage to the environment. In salmon producing countries such as Norway, USA, Canada and Chile, marine salmon farms (e.g. Figure 8) are constructed to ensure continuous supply of fresh fish (Per Heggelund, 1989).

Figure 7: Sustainable engineering science barge at Hudson River, Manhattan, USA (source: http://nysunworks.org)

Figure 8: Salmon farms at Vancouver, Canada (source: http://www.democracyinaction.org)

VLFS technology has also made possible future large human habitation on the ocean surface. The Lilypad Floating Ecopolis (Figure 9), proposed by the Belgium architect Vincent Callebaut, is an example of a visionary proposition to house the city population on a huge floating lily-shaped island. More concepts of floating cities are given in a recent paper by Pernice (2009). With more than half of the Netherlands's land area now below sea level, the Dutch have also proposed the concept of a floating town (Figure 10) comprising greenhouses, commercial centre and residential area.

Figure 9: Lilypad floating ecopolis (source: www.vincent.callebaut.org)

Figure 10: Visionary semi-aquatic town in the Netherlands (source: http://www.resosol.org)

3. Research studies on VLFS

In this paper, we will only focus on research studies carried out on the hydroelastic response, the structural integrity and the steady drift forces acting on the VLFS.

3.1 Hydroelastic response

Pontoon-type very large floating structures (VLFS) are like giant plates resting on the sea surface. As these structures have a large surface area and a relatively small depth, they behave elastically under wave action. This type of fluid-structure interaction has being termed hydroelasticity. Hydroelastic analysis is thus necessary to be carried out for the VLFS design in order to assess the dynamic motion and stresses due to wave action. There are two approaches used in performing the hydroelastic response of the VLFS, i.e. the frequency domain approach and the time domain approach.

Usually the frequency domain approach is used instead of the time domain approach when determining the hydroelastic response amplitude operator of the VLFS (modeled as a plate) because of its simplicity and ability to capture the pertinent response parameters in a steady state condition. In the frequency domain approach, the Laplace equation for the velocity potential is converted into a boundary value problem when solving for the motion of the floating body. The boundary conditions are the Neumann condition at the seabed and the wetted surfaces of the floating body, the linearised free surface condition and the radiation conditions at infinity. The earliest solution to this boundary value problem was given by John (1949, 1950) in which he used the Green's function within a boundary integral formulation to solve for the wave scattering from floating bodies. A detailed description of the linear wave theory was published by Wehausen and Laiton (1960) in their remarkable review article 'Surface Waves'. This review article contains benchmark solutions for wave-structure interaction problems. However, earlier works on the wave-structure interaction problems only consider the floating structure as a rigid body. With the increasing interest in VLFS as one of the future solutions for creating land from the sea, hydroelastic analysis on floating structure emerged as a new research area in the 1990s. To name a few, among the pioneers working on the hydroelastic theory of VLFS are Mamidipudi and Webster (1994), Yago and Endo (1996), Utsunomiya *et al*. (1998), Kashiwagi (1998) and Ohmatsu (1999).

The Mega-Float as shown in Figure 1 has a small draft compare to its length. The common approach is to model the entire floating structure by a single plate based on the classical thin plate theory (Utsunomiya *et al*. 1998; Kashiwagi 1998) while the water wave is modelled by using the linear wave theory. On the other hand, mega floating fuel storage modules, as shown in Figures 2 and 4, have larger draft to length ratios as opposed to the mat-like VLFS. This necessitates the modelling of the floating modules as a thick plate according to the Mindlin plate theory (Watanabe *et al*. 2000). The use of the Mindlin plate theory not only leads to more accurate prediction of the deflections, but it also provides a better prediction for the stress-resultants. Studies on hydroelastic interactions of two large box-like floating storage modules such as the one shown in Figure 4 have also been carried out recently by Tay *et al*. (2009). The modules affect each other due to diffracted waves, radiated waves and waves been squeezed into a channel formed by the floating modules being placed side-by-side.

The time domain approach is necessary in obtaining the transient response of the VLFS. The commonly-used approaches for the time-domain analysis of VLFS are the direct time integration method (Watanabe *et al.* 1998) and the method that uses the Fourier transform (Ohmatsu 1998; Kashiwagi 2000). In the direct time integration method, the equations of motion are discretized for both the structure and the fluid domain. In the Fourier transform method, we first obtain the frequency domain solutions for the fluid domain and then Fourier transforms the results for substitution into the differential equations for elastic motions. The equations are then solved directly in the time domain analysis by using the finite element method or other suitable computational methods. Researchers such as Kim and Webster (1998), Watanabe *et al*. (1998) and Kashiwagi (2004) have used the time-domain approach in solving the aircraft landing on the VLFS or wave impact problems.

The computational fluid dynamic (CFD) method, which involves solving the Navier Stokes equation, has also emerged as a popular research area due to its ability to handle vortex formations when wave is diffracted by sharp edges or attachment on the VLFS. For example, Lee *et al*. (2003) used the composite grid method to study the hydrodynamic interaction behavior between the submerged anti-motion device and the VLFS. They found that the vortex generated by the submerged plate as waves impinge on the structure increases the added mass and damping forces of the VLFS, thereby, decreasing the structural responses significantly.

3.2 Structural integrity (Functionality and Safety Criteria)

Functionality and safety criteria are key issues that dominate the structural design of the VLFS. Taking the Mega-Float as an example, the functional criterion that dominates the Mega-Float design is the effect of the hydroelastic responses on the sensitive instrument landing system, precision approach pass indicator, and future air navigation system (Suzuki 2005). Hence the Mega-Float should have sufficient stiffness to minimize the hydroelastic response due to wave action. The safety criterion is to ensure that the Mega-Float is sufficiently strong to withstand the structural components stresses due to applied live loads and environmental loads. Suzuki *et al*. (2006) reported that the stresses in the structural components and the vertical movement of the airplane on the floating runway depend significantly on the structural wave propagation, i.e., the hydroelastic response. Suzuki (2005) claimed that excessive deformation, motion, and vibration induced on the VLFS would disrupt the serviceability of the Mega-Float as a floating runway whereas cyclical loading due to wave slamming might result in fatigue of the structural components. The excessive structural response could also lead to the sinking of the floating structure due to progressive flooding and drifting of the floating structure due to the failure of dolphin-fender system. More sophisticated hydroelastic analyses have also been done for a complete 3D floating structure, in order to obtain the deflections and stresses for the secondary structural components in the VLFS (Seto *et al*. 2003) as well as the local strength of the structural members (Sasajima 1999; Inoue *et al*. 2003).

3.3 Drift forces for mooring system design

The design of a mooring system requires the determination of wave drift forces acting on the VLFS. There are two well known methods for computing the wave drift forces, namely, the near-field method (Pinkster 1979) which is based on the direct pressure integration method and the far-field method (Utsunomiya *et al.* 2001, Kagemoto and Yue 1986, Maruo 1960) based on the momentum-conservation principle. While both methods are able to predict the drift forces reasonably well for a single VLFS, the far field method possesses some limitations when two or more floating modules are placed adjacent to each other such as the case for the FFSF shown in Figure 4. This is because the far-field method gives only the total forces acting on all floating modules, thus the forces acting on individual module could not be obtained. On the other hand, the near-field method proposed by Pinkster (1979) gives individual force on each floating structure although the computations are rather complicated because various components must be evaluated, such as the flow velocity on the wetted surface and the relative wave height along the waterline of a ship. Kashiwagi *et al.* (2005) also adopted the near-field method to compute the interaction of two ships which are arranged side-by-side in waves. Relative good agreement is found between Kashiwagi *et al*.'s (2005) computed and experimental results.

4. Development of VLFS technoloy

Presented herein are the technological developments of VLFS, focusing on the design of mooring systems, methods for mitigating the hydroelastic responses and connector designs.

4.1 Mooring systems

The mooring system ensures that the VLFS is kept in position so that the facilities installed on the floating structure can be reliably operated as well as to prevent the structure from drifting away under critical sea conditions and storms. A freely drifting very large floating structure may lead to not only damage to the surrounding facilities but also to the loss of human life if it collides with ships.

The station keeping system of a floating structure may be grouped into two main types: (1) the mooring lines type (see Figures 11(a) and 11(b)), and (2) the caisson or pile-type dolphins with rubber fender system (see Figure 11(c)). The former type uses chains, wire ropes, synthetic ropes, chemical fiber ropes, steel pipe piles, and hollow pillar links. These mooring systems are used for VLFS operating in deep sea such as the tension leg floating wind farm and the floating salmon farm (see Figure 8). However, the motions of a floating structure become large when the length of mooring line is rather long. Especially in deep seas, the tension leg system (see Figure 11(b)) is adopted to which the pretension is applied to the mooring line in order to restrain heaving motion. In such a station keeping system, it is difficult to restrain the horizontal motion and usually the mooring lines experience significant tension forces.

(b) Chain/Cable (b) Tension Leg (c) Rubber fender-Dolphin

Figure 11: Various Types of Mooring Systems

The rubber fender-dolphin mooring system was first adopted for the two floating oil storage bases at Kamigoto and Shirashima islands in Japan. The mooring system has since been used for other facilities such as floating piers, floating terminals, floating exhibition halls, floating emergency bases, and floating bridges. The rubber fender-dolphin type is very effective in restraining the horizontal displacement of the floating structure. As the large size rubber fenders are able to undergo a large deformation (of up to approximately one-third of their lengths), a considerable amount of the kinetic energy of the floating structure can be absorbed.

4.2 Mitigation of Hydroelastic response

Various methods have been proposed by engineers to minimize the hydroelastic response of the VLFS. One of the earliest methods is by constructing bottom-founded breakwater close to the VLFS as was done for the Mega-Float. Studies by Utsunomiya *et al*. (2001) and Ohmatsu (1999) showed that the bottom-founded type breakwater is very effective in reducing the hydroelastic response as well as the drift forces. However, such type of breakwater still possesses some drawbacks that include massive construction material requirements, difficulty in construction, occupying precious sea space, difficulty in removing the breakwater if the VLFS is to be relocated elsewhere, not environmentally friendly, and the reflected waves from the breakwater could result in coastal erosion.

The floating box-like breakwater moored with mooring lines has been proposed as an alternative to the conventional bottom-founded type breakwater for protecting VLFS from a severe sea. Floating breakwaters do not disrupt the ocean current flow and cause relatively little damage to the seabed. Furthermore, the floating box-like breakwater (being the most common type) constructed around the FFSF as shown in Figure 4 could also function as collision and oil spill barriers. Besides the single box-like floating breakwater design, floating breakwaters of different configurations and cross-sections have been proposed in order to enhance the efficiency of the breakwater in attenuating the wave forces.

As the use of breakwaters in attenuating the wave forces impacting on the VLFS is relatively expensive and requires more time for construction, engineers are motivated to invent anti-motion devices that are attached to the VLFS. The earliest form of anti-motion devices is that of a submerged horizontal (Ohta *et al*. 1999; Watanabe *et al*. 2002) or a vertical plate (Ohta *et al*. 1999) attached to the fore-end of the VLFS. The submerged plate attachments are able to dissipate the incident wave energy and reduce the incident wavelength by generating breaking wave, wave fission, and vortices. Takagi *et al*. (2000) proposed a submerged box-shape anti-motion device attached to the fore-end of the floating structure.

Research studies such as those carried out by maeda *et al.* (2000), ikoma *et al*. (2002) and hong *et al*. (2006) investigate the use of oscillating water column (owc) anti-motion device in reducing the hydroelastic response of the VLFS. Such a device is similar to the submerged anti-motion device but could achieve more reductions in the hydroelastic responses due to the capability of the owc air chamber in absorbing wave energy. However, the attachment of the owc anti-motion device would result in an increase in the drift forces.

In order to reduce the hydroelastic response due to wave slamming or air-craft take-off/landing load, Pinkster (1979) pioneered the use of air-cushion for reducing the large displacements and drift forces. Van Kessel *et al*. (2007) and Ikoma *et al*. (2009) carried out extensive studies on the effect of having different numbers of air-cushion units for reducing the motions of the VLFS.

The hybrid type anti-motion device which involves a combination of floating breakwater, submerged plate anti-motion device and OWC chamber is proposed for better reduction in the hydroelastic response of VLFS. Shigemitsu *et al*. (2001) proposed a hybrid wave load reducing system, which consists of a floating breakwater placed in front of the Ecofloat (a combination of seaport and airport with sustainable power plant) whereas the Corporation for Advanced Transport and Technology in Japan has also proposed the subplate VLFS, which consists of a submerged plate anti-motion device attached to the fore-end and protected by submerged plate floating breakwaters.

4.3 Connector Designs

VLFS is usually constructed in modules due to its massive size. The modules are fabricated in shipyard, and then connected on site in the sea by welding or by using rigid connectors. More recently, Fu *et al.* (2007) and Wang *et al*. (2009) proposed the use of hinge or semi-rigid connectors instead because they found that the non-rigid connectors are more effective in reducing the hydroelastic response as compared with the rigid connectors. There have been various connector designs proposed and a review paper by Lei (2007) gave a wide range of these connector systems. However, there is still work to be done on developing a robust and economical connector system for very large floating modules.

4.4 Other Developments

The shapes of the VLFS may take on more arbitrary geometries such as the irregular-shaped floating island in the han river (see Figure 5) instead of the conventional rectangular shape VLFS. Various researchers have also considered VLFS of different shapes that could reduce the hydroelastic responses. For example, okada (1998) has investigated VLFS with different edge shapes and confirmed that the notched edge is able to reduce the propagation of deformation over the VLFS. With the view to reduce the hydroelastic response, VLFS with moonpools and different stiffnesses are proposed and they are found to be very effective in reducing the hydroelastic response of the VLFS when the wave length is small. Wang *et al.* (2006) have also introduced the innovative *gill cells* in very large floating container terminal in order to provide an effective solution for reducing large differential deflections of a VLFS under uneven static loading.

5. Concluding remarks

Presented herein is a summary of the applications, research and development of the VLFS. Various existing VLFSs are presented and some potential applications of VLFS as urban agriculture and future human habitation are highlighted. The research developments of the VLFS are also presented with main emphasis on the hydroelastic response, structural integrity and steady drift forces. The conventional method in performing the hydroelastic analysis by using the frequency and time-domain approaches and a more recent method based on cfd are briefly discussed. Research studies on functionality and safety criteria that affect the structural integrity of the VLFS as well as the near-field and far-field method used to obtain the steady drift forces of the VLFS are also presented.

The technological developments on the mooring system, anti-motion devices and connector designs of VLFS over the past decades are highlighted. Two different types of mooring system are used for the VLFS, i.e. The mooring lines type and the caisson/dolphin type. The mooring lines type is usually used for VLFS deployed in deep water whereas the caisson/dolphin type for VLFS in shallow water. Methods used for mitigating the hydroelastic responses include the bottom-founded and floating breakwaters, submerged and owc anti-motion devices, air cushion, and the hybrid type anti-motion devices. Connectors used to join modules of VLFS have also evolved from fixed type to semi-rigid and hinge type. The semi-rigid and hinged type connectors are also found to be effective in reducing the hydroelastic response of the VLFS.

Future research studies on VLFS may include (a) the effect of variable water depth and/or wave short-crestedness on hydroelastic response of VLFS equipped with anti-motion devices, (b) on-sea experiment for validation of the effectiveness of anti-motion devices in real environmental conditions, and (c) the effect of slowly varying drift forces on the hydroelastic response of VLFS equipped with anti-motion devices.

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