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Figure 3. *Petronas Satu* on location (image courtesy of Petronas).

Arun Duggal, SOFEC Inc., USA, looks at the importance of mooring systems for FLNG units.

The floating LNG (FLNG) facility concept has helped revolutionise the development of LNG production from gas fields, both nearshore and in deeper water. The concept has been around for over 20 years, but in the past 10 years has been taken to the engineering, procurement and construction (EPC) level, culminating in Petronas' *PFLNG Satu* producing and offloading LNG earlier this year, and the completion of fabrication of Shell's *Prelude*. Four other floating facilities are in various stages of completion. For instance, the production systems for Exmar's FLNG unit have been commissioned, but the facility is looking for a deployment location; Petronas' *PFLNG2* and the *Golar Hilli*, meanwhile, are both at various stages of fabrication; and another FLNG unit was recently awarded to the TJS Consortium for the ENI Coral South field offshore Mozambique, with an expected first LNG date in approximately five years. One more FLNG unit is currently under consideration for final investment decision (FID) this year: the *Golar Fortuna FLNG* for a field in Equatorial Guinea.

A key technology for FLNG units is the mooring system that maintains the system on location for the duration of the project typically on the order of 20 – 30 years. FLNG units are able to leverage the technology developed for floating production, storage and offloading (FPSO) vessels over the past 30 plus years, specifically the development of a number of single-point mooring systems that have been developed for over 150 FPSOs. These systems have been installed in a wide range of water depths (20 – 3000 m) and environmental conditions (West Africa, the North Sea and the Gulf of Mexico), and for a wide range of reservoir and fluid processing systems. To date, all FLNG units have utilised single-point mooring systems except the Exmar FLNG unit that was designed to be jetty-moored.

Single-point mooring systems, and more specifically turret mooring systems (and tower yoke mooring systems for shallow water), are both load-transfer and fluid-transfer systems. The turret mooring system (which can be both internal to the vessel or external) is the main interface between the floating facilities (hull and topsides) and the subsea production systems, including the riser and umbilical systems that interface between the turret and the subsea equipment. This makes the turret mooring system the equivalent of the central nervous system for the development, and optimum design requires proper definition of all interfaces.

The load-transfer portions of the turret provide the stationkeeping performance required to ensure the integrity of the riser and umbilical systems under all environmental conditions. The weathervaning capability comes from the bearing system that is used to allow the vessel to align itself to the predominant environment and transfer loads from the moorings to the vessel and vice versa.

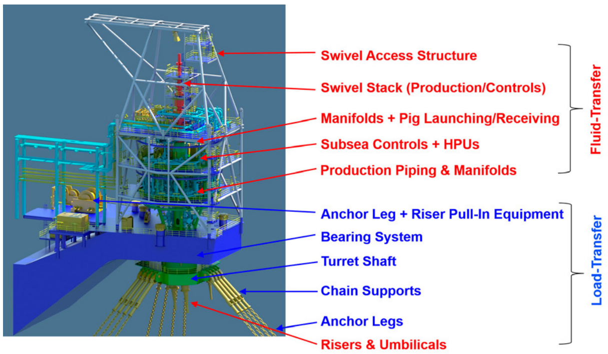

Figure 1. Schematic of an External Turret Mooring System.

The fluid-transfer system primarily provides pressure and flow control of the incoming fluids to the topsides and to export or re-inject fluids from topsides to the reservoir. The key component within the fluid-transfer system that allows the system to weathervane and transfer fluids from the earth-fixed riser and umbilical system to the rotating process equipment on the vessel is the swivel stack. The swivel stack contains several swivels to allow the transfer of gas, liquids, power and signals. Figure 1 shows the external turret for *Petronas FLNG2*, illustrating the various components of a turret mooring system.

The ability of the FLNG unit moored with a turret mooring system to weathervane allows the vessel to align itself with the predominant environmental direction. This results in reduced loads on the system during extreme storm conditions, and provides flexibility for the approach berthing, offloading and de-berthing operations of the LNG carrier that will typically offload in a side-by-side (SBS) arrangement. In open seas, the berthing and de-berthing operations of the offloading carrier to and from the FLNG unit is a critical operation that can be aided by aligning the host vessel to the environment in the most favourable orientation. This tends to occur naturally, but if not, can be achieved by controlling the vessel heading using a thruster on the stern of the FLNG unit. This results in higher availability for offloading while ensuring reliability of the operation.

The technology described above is mature, having been developed for FPSOs over the past 30 years. FLNG facilities vary greatly in size depending on processing and storage capacity. From the fluid-transfer perspective, FLNG systems are typically less complex than the requirements for large FPSOs, with similar pressure and temperature requirements. Swivel systems for gas are very mature so no new technology is required.

Figure 2. The Tower Yoke moored *Hoegh Lampung FSRU* (image courtesy of Hoegh LNG).

Some of the smaller FLNG systems, such as the *Golar Hilli*, *Petronas FLNG Satu*, and *Petronas FLNG2*, are similar in size to a very large crude carrier (VLCC) based FPSO, and are in relatively moderate environments. Therefore, they have utilised a mooring system with components similar to a moderate to large FPSO. For the two large FLNG units, *Prelude* and *Coral South*, the large size of the vessel hull (up to 500 m long, 70 m wide and 40 m deep), extensive process equipment over the entire length (up to 60 m high), and harsh environmental conditions (both are in active cyclone regions), the load-transfer component of the turret (primarily the bearing, anchor leg system and the structure) are much larger than that typically used for FPSOs.

The technology described above is equally transferable for the mooring of floating storage and regasification units (FSRUs) when jetty mooring is not deemed practical or becomes expensive. With the expected sharp increase in FSRUs worldwide, as part of the distribution systems for large amounts of LNG expected on the market, this is seen to be a growing market for mooring systems. One option is the use of a tower yoke mooring that has been employed on the *PGN FSRU Lampung*, offshore Indonesia. This system provides the ability to permanently moor the vessel on location for all seastates up to the 100 year environmental conditions, and to allow offloading in seastates up to the 10 year environmental conditions with 100% availability. The added advantage of a tower yoke mooring is that the gas is transferred to the seabed using a rigid conductor with the flexible lines being suspended between the vessel and the tower as shown in Figure 2.

Figure 4. The Petronas FLNG2 Turret Mooring System at the Turret Fabrication Yard.

Project specific experiences

Over the past 15 years, SOFEC – a member of the MODEC Group – has been active in studying the specific requirements and developing technology for both the mooring of, and offloading from, FLNG units. SOFEC has participated in several collaborative FEED studies with several large contractors (including MODEC), and major oil companies to define the requirements for mooring FLNG units, and has been successful in being awarded the EPC of the turret mooring for three of the first five FLNG units to date.

This section provides a brief summary of each of the three turret mooring systems, focusing at some key parameters that define the requirements for the turret mooring system, and also some milestones from the project execution schedule.

Petronas FLNG Satu

FLNG Satu has been designed to operate at several fields in 70 – 200 m of water, offshore Malaysia. The turret was designed to accommodate the changes in riser and umbilical count, total gas flowrate, and loading on the system for a range of deployment locations (and reservoirs) and water depths.

The FLNG unit is designed to have a 20 year life with the first deployment (Phase 1) for approximately five years in approximately 75 m of water. For this deployment, the gas is fed from a platform so the external turret receives the gas through one 10 in. riser. The FLNG unit is based on a hull that is 300 m long, 60 m wide and 33 m deep, very similar in size to a VLCC hull. The production capacity is 1.2 million tpy of LNG, with a maximum gas throughput of 230 million ft^3/d at 130 bar.

The external turret mooring system is designed to accept a maximum of three 10 in. risers and three umbilicals, and is designed with a 12-leg anchor leg system, arranged in three groups of four. The 100 year design seastates are approximately 8 m significant, with a maximum wind speed of 30 m/sec. The relatively small vessel size and the moderate environment allowed the use of a moderately sized external turret, very similar to turrets supplied for FPSOs. The total turret weight was approximately 1000 t.

The FEED for *FLNG Satu* started in 2011 and the contract was awarded in December 2012. The turret was delivered 18 months later in 2014. The FLNG unit was installed at the site in mid-2016, and the first LNG offload was in 2Q17. The facility is pictured in Figure 3.

Petronas FLNG2

PFLNG2 will be located on the deepwater gas field Rotan, offshore Malaysia, in approximately 1250 m of water. The environmental conditions are similar to *PFLNG Satu*. The FLNG unit is also designed to be deployed at various locations ranging in water depth from 500 to 1500 m. SOFEC is supplying a large external turret for this FLNG unit that is 333 m long, 64 m wide and 31 m deep, with a production capacity of 1.5 million tpy with a maximum

Figure 5. *The SOFEC Very Large Turret (VLT).*

gas throughout of 300 million ft^3/d at 100 bar, with a design pressure of 255 bar.

The SOFEC external turret for *FLNG2* features a high integrity pressure protection system (HIPPs) on board the turret to provide protection to the process equipment downstream of the valves. This also allows a specification break on the piping and swivels downstream of the HIPPs valves. The turret also allows for 2000 bpd of rich MEG injection and supports a total of four 10 in. risers and three umbilicals. The anchor legs are arranged in a 3 x 4 arrangement with the deepwater locations using chain and polyester rope as the main components, while the shallower water depths use chain and spiral strand wire rope. The turret is almost complete and awaiting delivery to the shipyard for integration and commissioning. Figure 4 presents a picture of the turret at the turret fabrication yard.

The project started a FEED competition exercise in 2012 and awarded the EPC contract in 2014. The original schedule required a turret delivery in 26 months, but the client has since changed the first gas milestone on the project schedule. SOFEC is now expecting to deliver the turret by the end of 2017.

Coral South FLNG

This project was recently sanctioned in June 2017, with the project award being made to the TJS Consortium, comprising of TechnipFMC, JGC Corp., and Samsung Heavy Industries (SHI). SOFEC is a subcontractor to the TechnipFMC-JGC joint venture (JV), and will supply a large internal turret based on its very large turret (VLT) technology that has been under development since the early 2000s.

The FLNG unit will be based in approximately 2000 m water depth off the coast of Mozambique. This will be the first large offshore gas development in East Africa. The region is subjected to complex metocean conditions with monsoons, swells from the Indian Ocean, and cyclonic storms, with a 100 year wave height of approximately 13 m and 33 m/sec. wind speed, and a 10 000 year wave height of approximately 17 m with a wind speed of approximately 50 m/sec.

The FLNG unit is based on a vessel hull with dimensions of 433 m length, 64 m wide and 38.5 m depth. The rated capacity of the unit is 3.4 million tpy with a maximum gas throughput of 600 million ft^3/d at 143 bar. The design pressure is approximately 400 bar.

The SOFEC turret is a large internal turret with a main bearing system that is replaceable in situ. The bearing diameter is approximately 25 m and the turret employs a 20-leg taut mooring system arranged in four groups of five legs each (4 x 5). The anchor leg configuration utilises chain and polyester rope, anchored with a suction pile. The turret supports eight 9 in. flexible risers, and four umbilicals. The turret also provides injection of up to 30 m^3/hr of lean MEG, and 10 m^3/hr of water production. The upper turret is designed for ease of maintenance and operation with three large decks to support the piping, manifolding, swivels, and the electrical room. The turret has a total turret weight of approximately 7500 t. Figure 5 presents a schematic of a SOFEC VLT.

Coral South FLNG started as a FEED competition in 2014 with a contract award in 2017. The turret delivery is scheduled in 35 months and the vessel is expected to be producing LNG in five years.

Conclusion

With FLNG units becoming a demonstrated and viable technology for the production of LNG, this opens up the development of both stranded and new gas fields for development worldwide. Leveraging mature technologies from the FPSO industry, such as single-point mooring systems, results in a reliable and cost-effective means to provide a safely moored vessel in environmental conditions with a return period up to 10 000 years, and provides high availability for offloading. The projects undertaken and currently underway demonstrate the feasibility of the technology transfer from FPSO mooring systems to a wide range of FLNG systems worldwide. **LNG**