Sloshing in membrane LNG carriers and its consequences from a designer's perspective

T. Gavory, P.E. de Seze
Marketing dep't, Gaztransport & Technigaz
Liquid motion dep't, Gaztransport & Technigaz
Saint-Rémy-lès-Chevreuse, France

ABSTRACT

The worldwide utilisation of natural gas has led producing countries to look for transportation solutions. Marine transportation becomes economically feasible for long distances or when pipe laying becomes unpractical. In order to ship natural gas in sufficient quantities to make a complete energy supply project viable, it is liquefied at -163° C thereby reducing its volume by a factor of 600.

Several containment technologies have been implemented, including SPB, Moss and Membrane. Contrary to its two main competitors, where the insulation is installed on the outer part of a self-supporting tank, the membrane systems (the only currently used designs on board LNG carriers are exclusively developed by Gaztransport & Technigaz) incorporate a liner fitted directly onto the double hull. One of the main characteristics of this type of system is that it transfers to the double hull the loads induced by liquid motions inside the tanks.

This hydrodynamic phenomenon, also known as sloshing, can lead to high magnitude impacts on the walls with potential consequences on the containment system response. This is why sloshing is extensively studied in the LNG shipping industry and more especially in GTT, where dedicated high-tech numerical tools and testing facilities have been developed for many years.

At the same time, we have recently observed a rapid growth in the number of membrane LNG carriers in service, their cargo capacity and the variety of operating procedures (spot market, offshore regasification, etc). In parallel, a few unexpected incidents related to sloshing impacts have recently been recorded. No such incident had been observed since those isolated ones observed on former designs in the late seventies.

Research and development effort into the sloshing phenomenon has never been so intense, particularly within GTT, and the overall knowledge on this subject has reached an unprecedented level. Particularly, the feed-back and lessons learned from these incidents are of inestimable interest for the scientific community, and help increase the phenomenon's knowledge. However, some particularities of these incidents and thus of the sloshing phenomenon itself, still have not been as yet explained to our entire satisfaction.

Given the strong expectations from the industry to improve understanding and thus better tackle the sloshing phenomenon and its consequences, this paper will introduce most of the research studies that have been performed recently or which are currently in progress as well as a major evolution of the methodology for sloshing assessment. Each of these items will be then described and discussed in detail during dedicated ISOPE presentations.

KEY WORDS: Sloshing; LNG; membrane containment system; model tests; numerical simulations; sloshing incidents.

INTRODUCTION

Over since man started to sail the oceans, he has shipped different kinds of liquids with him, whether it was for the crew's own consumption or for commercial purposes. As the size of the vessels increased, amphorae became barrels and the shipping routes lengthened and diversified, but still the amount of liquid to be loaded was limited, due to the fact that it was stowed in casks or tuns (hence the term "tonnage") in the ship's hold. This shipping mode was the prevailing one until the second half of the 19th century. However, it had some important drawbacks:

- The barrel's weight: a standard empty 40-US-gallon wooden barrel weights 29kg, which represented 17% of the total weight of a full barrel if filled with water, and nearly 20% of the total weight if filled with petroleum oil (Chisholm, 1911).
- Leakages of a wooden cask could be quite important and either lead to non-acceptable product waste or even worse place the vessel at risk, in case of oil transportation, for example.
- The barrel's cost had a strong impact on the profitability of liquid transportation by sea. For example, in the early years of the Russian oil industry, barrels accounted for half the cost of petroleum production (Tolf, 1976).

Despite these problems, it was preferred to load liquid in casks rather than to transport it in bulk, because the available technology was not sufficiently developed to support the idea of carrying bulk liquids. Among the problems caused by shipping liquid in bulk in the earlier ships, we have identified three main ones:

- In the early days, ships were made of timber, and of course so were their holds. As a consequence, these holds were not liquid tight enough to avoid any risk of spillage or important cargo loss. Leaks were a problem as well for wooden casks, but the spill amount was in that case more limited and could be confined.
- When the ships had to be loaded or discharged, casks or barrels could be handled with ordinary cranes or rolled by dockers, and then stored in a standard warehouse. Bulk liquid cargo has to be pumped to or from shore, and dedicated storage facilities are required relatively close to the berth. Efficient pumps and piping systems were simply not available until quite recently, especially for sensitive liquids such as hydrocarbons.
- Finally, large free surfaces of liquid have a strong influence on ship stability. Ship motions will make the liquid slosh, and sloshing will in return affect the ship motions, enough to potentially affect the overall stability of the vessel and causing capsize. At times when naval architecture and hydrodynamics relied exclusively on experience, ship design was not developed enough to allow such a loading mode.

But economics always has the last word, and the need for oil companies to find cheaper ways to ship their products to the end users led some bolder or cleverer naval architects to finally successfully develop the first oil tankers, in the late 1870ies (Chisholm, 1911 and Woodman, 1998).

Those ships had two iron tanks carrying a total of about 240 tons of kerosene, aft and fore of the midship engine room. The ship had a beam of 8.2m, and the tanks' breadth was close to the ship's beam, so oil sloshing from side to side still caused stability problems. This was partly solved in 1883 with the appearance of subdivided holds, especially in the transverse direction, by adding a longitudinal bulkhead in the design (Tolf, 1976). This approach of dividing the ship's storage space into smaller tanks virtually eliminated free-surface problems (Huber, 2001).

LNG TRANSPORTATION BY SEA

First LNG carriers' developments

Nowadays, various liquids are shipped in bulk: crude and refined oil, LPG, LNG, chemicals, edible liquids, in tanks of various volumes and technologies (due to potential requirements for monitoring of temperature, pressure and atmosphere). Among them, LNG is one of the cargoes which require the highest technology tanks and vessels. Indeed, the maritime transport of natural gas requires that the gas be liquefied first. Liquefaction reduces the volume of the gas by a factor of 600 and thus makes it possible to transport large quantities of gas by ship. However, for simple physical reasons, liquefaction cannot be made by simple compression, as for butane. Natural gas must be cooled and, to ensure the stability of the liquid at atmospheric pressure, it must be brought down to -163°C. Because of all these difficulties, the history of shipping LNG in bulk is much more recent, and started only in the late 50ies.

The first LNG carrier, as we call them now, was developed by William S. Morrison and made her maiden voyage on January 25th 1959, between Lake Charles (USA) and Canvey Island (UK). This vessel, named Methane Pioneer, had a capacity of 5,000m^3 distributed over 5 tanks made of Aluminium Alloy with Balsa wood insulation on the outside.

Figure 1: Methane Pioneer at berth

In parallel, French shipyards and gas companies worked together to develop and build a prototype, called Beauvais, with three tanks each of a different kind, for a total capacity of 640m^3, with the aim to gain experience and knowledge in the mastering of LNG tank design and construction. These two first-of-a-kind vessels led to the delivery of the first "commercial" LNG carriers, Methane Princess and Methane Progress in the US, 28,300m^3 each, using nine Aluminium alloy tanks with Balsa wood / fibreglass insulation in 1964, and the Jules Verne in France, 25,840m3 of LNG stored in seven 9% Nickel-Steel alloy tanks with Perlite and "Klegecell" (expanded vinyl chloride with a density of 55kg/m3) in 1965.

Figure 2: Jules Verne LNG Carrier

A few other LNG containment technologies were developed after these two successful attempts, but it is during the seventies that two main technologies have taken the lead and are still sharing the LNG shipping market 40 years later: the membrane integrated tanks firstly developed by two French companies (Technigaz and Gaz Transport) who merged in 1994 to set up Gaztransport & Technigaz (GTT) and the spherical-type independent tanks developed by the Norwegian company Moss Maritime. GTT owns and develops all patents related to membrane containment systems currently installed on LNG carriers, which constitute more than 2/3 of the fleet in service, and more than 80% of the LNG carriers' orders. Continuous improvements of these two techniques during the last four decades have permitted increases in the ship's cargo capacity while reducing the number of tanks. At the beginning of the new millennium, the standard capacity of an LNG carrier, whether it was of spherical or membrane type, was in the range of 138,000m^3 divided into 4 tanks (Jean, 1998), and the first of the 14 ordered giant LNG carriers (>260,000m^3 in 5 tanks) was delivered in 2008.

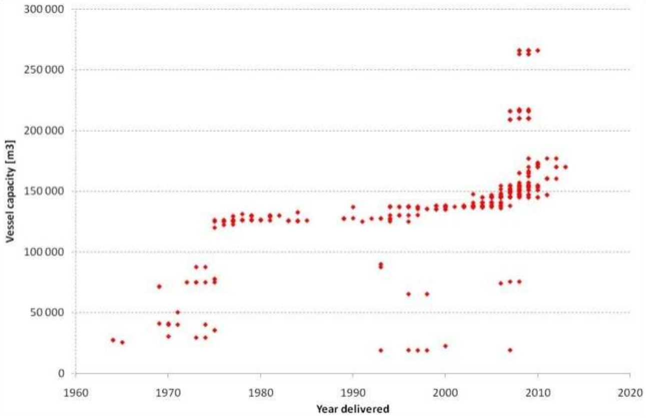

Figure 3: LNGC Fleet capacity evolution from 1960 to 2015

The LNG carriers of capacity greater than 200,000m^3 constitute a fleet of 45 vessels and their tanks are all fitted with membrane containment systems. The membrane technology consists of a cryogenic liner which is anchored to the structure of the vessel; more precisely to its inner hull as LNG carriers are double hull vessels. This double hull is particularly important for LNG carriers as the volume of ballast required is important (80% of the cargo weight) in order to maintain these rapid vessels (usually 19.5 knots) at almost a constant draft. The double bottom and longitudinal double hull are used as ballast capacities. The inner hull therefore handles the loads caused by the pressure of the liquid height, the ship bending moment and the thermal contraction of the containment system. The IMO Gas Code requires in the case of membrane technology to have two barriers able to hold tightly the liquid cargo in order to prevent the low temperature liquid to reach the hull structure should a significant leak occur through the primary membrane. The hull being made of ordinary steel, it would become brittle if LNG came into contact with it. Therefore, all vessels with membrane containment system have two membranes, a primary membrane in contact with the LNG and a normally redundant secondary membrane which ensures that LNG is kept away from the inner hull in case of a primary failure. The containment system also presents insulating characteristics able to maintain a temperature acceptable for the steel inner hull and able to minimize the heat transferred to the cargo thus minimizing its evaporation as Boil Off gas. The most extreme conditions have been retained to set the criteria and so the hull temperature is considered in degraded conditions with LNG on the secondary membrane and with the lowest design external temperatures (usually –18°C air temperature and 0°C sea water temperature). Most of the heat transferred to the cargo results in Boil Off whose rate shall be maintained below a design value (usually equivalent to 0.15% of the cargo volume per day in the highest design external temperatures, usually +45°C air temperature and +32°C sea water temperature). As for mechanical stresses, this insulation must withstand the thermal cycles and resist the loads created by the liquid static and dynamic pressure, and transfer it to the inner hull structure.

Two systems, No 96 and Mark III, dominate the membrane market while a third, CS1, has been installed on three vessels up to now.

No 96

The No 96 system is a cryogenic liner made of two identical metallic membranes and two independent insulation layers *(see Figure 2)*. The primary and secondary membranes are made of invar, a 36% nickel-steel alloy, 0.7 mm thick. The primary membrane contains the LNG cargo, while the secondary membrane, identical to the primary, ensures a 100% redundancy in case of leakage. Each of the 500-mm wide invar strakes is continuously spread along the tank walls and is evenly supported by the primary and the secondary insulation layers.

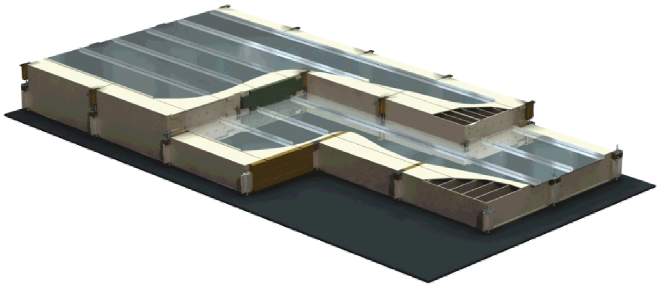

Figure 4: No96 Containment System

The primary and secondary insulation layers consist of a load bearing system made of prefabricated plywood boxes filled with expanded perlite. The standard size of the boxes is 1 m x 1.2 m. The thickness of the primary layer is adjustable from 170 mm to 250 mm, to match any B.O.R. requirement; the typical thickness of the secondary layer is 300 mm. The primary layer is secured by means of the primary couplers, themselves fixed to the secondary coupler assembly. The secondary layer is laid and evenly supported by the inner hull through load-bearing resin ropes, and fixed by means of the secondary couplers anchored to the inner hull.

Mark III

The Mark III system is a cryogenic liner composed of a primary metallic membrane positioned on top of a prefabricated insulation panel including a complete secondary membrane *(see Figure 3)*. The primary membrane is made of corrugated stainless steel 304 L, 1.2 mm thick. It contains the LNG cargo and is directly supported by and fixed to the insulation system. Standard size of the corrugated sheets is 3 m x 1m. The secondary membrane is made of a composite laminated material: a thin sheet of aluminium between two layers of glass cloth and resin. It is positioned inside the prefabricated insulation panels between the two insulation layers.

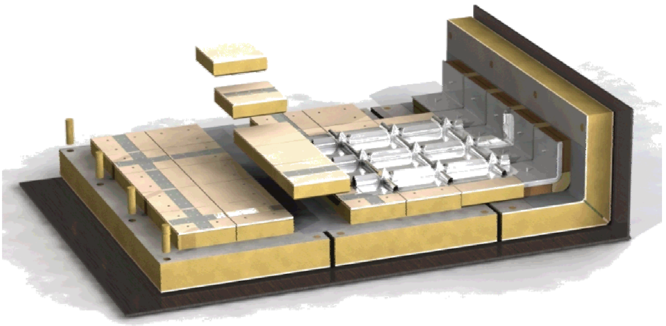

Figure 5: MarkIII Containment System

The insulation consists of a load-bearing system made of prefabricated panels in reinforced polyurethane foam including both primary and secondary insulation layers and the secondary membrane. The standard size of the panels is 3 m x 1 m. The thickness of the insulation is adjustable from 250 mm to 350 mm to fulfil any B.O.R. requirement. The panels are bonded to the inner hull by means of resin ropes which serve a double purpose: anchoring the insulation and spreading evenly the loads.

CS1

The CS1 system is a cryogenic liner composed of a primary metallic membrane positioned on top of a prefabricated insulation panel including a complete secondary membrane *(see Figure 4)*. The primary membrane is made of invar, a 36% nickel-steel alloy, 0.7 mm thick. The primary membrane contains the LNG cargo. Each of the 500 mm wide invar strakes is continuously spread along the tank walls and is evenly supported by and fixed to the insulation. The secondary membrane is made of a composite laminated material: a thin sheet of aluminium between two layers of glass cloth and resin. It is positioned inside the prefabricated insulation panels between the two insulation layers.

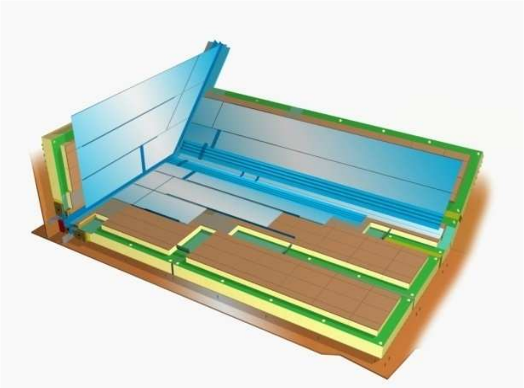

Figure 6: CS1 Containment System

The insulation consists of a load-bearing system made of prefabricated panels in reinforced polyurethane foam including both primary and secondary insulation layers as well as the secondary membrane. The standard size of the panels is 3 m x 1 m. The panels are bonded to the inner hull by means of resin ropes which serve a double purpose: anchoring the insulation and spreading evenly the loads (Deybach, 2003)

Sloshing in LNG Carriers: first evidence at sea.

The increase in tank size has raised again the issue of sloshing, which had been solved in oil tankers precisely by reducing the tank size. So one should wonder why go the opposite way from what was done in the past, knowing that this phenomenon would have to be tackled again? First, LNG is not oil. It cannot be handled so easily, mainly because it has to be shipped at its boiling temperature of -163°C. As a consequence, the main objective of an LNG containment system is to prevent the cryogenic liquid from reaching the ship's steel structure while keeping the amount of generated boil off gas (natural evaporation of LNG in the tanks) to a reasonable value from commercial and cargo handling management reasons (typically ≤ 0.15%V/day). The easiest solution to reduce the boil off is to limit the ratio between the containment area (the hot source) and the cargo volume (the cold source) by increasing the tank volume. For LNG tanks, sloshing may first be an issue in terms of dimensioning of the pump tower, the steel structure located in the tanks and supporting the cargo handling equipment (pumps, filling and discharge pipes, float level gauge, temperature sensors, etc), which is true for all types of tanks. Furthermore, the membrane containment system being a liner directly fitted on the inner hull, the sloshing loads are transferred to the ship's steel structure through the membrane anchoring elements. The containment system actually filters these loads and has to withstand only a fraction of it. The main work of the membrane designer, as far as sloshing is concerned, is to develop a system able to transfer the loads without damage on the CCS, while maintaining its flexibility and low weight characteristics. On the other side, the main feature of the independent type-B tanks is that the loads are to be sustained by the tank itself, which is self-supporting, and not by the strong steel structure of the vessel. This is one of the reasons why its metallic barrier (aluminium or 9% nickel-steel alloy) is rather thick (a few centimeters in some areas) and as a consequence quite heavy.

The potential consequences of this hydrodynamic phenomenon on membrane tanks were first observed in 1969 onboard the *Polar Alaska*, one of two sister-ships built in Swedish Kockums shipyard for Phillips Petroleum and Marathon Oil for trading LNG from Alaska to Japan. Those two 71,500m^3 LNG carriers were the first fitted with Gaz Transport containment system, called at that time No82, and were delivered both during last quarter of 1969. During the Polar Alaska's first ballast voyage, the phenomenon of resonance between the ship's movement and the liquid cargo's movement caused waves to break inside the first tank toward the bow where the filling level was in the range of 20% of the total tank volume. Indeed, in order to limit the thermal stress variations in the thin Invar barriers, and to reduce as much as possible the gas return to the onshore terminal during loading, which would occur if tanks were allowed to warm up during the ballast voyage, it had been decided to spray the tanks with LNG to keep them cold. This spraying was done using a reserve of liquid kept in tank n°1. The necessary liquid heel to keep all the tanks cooled was about 20% of the total capacity of the tank.

Courtesy Sovcomflot

Figure 7: ex-Arctic Tokyo now SCF Arctic

During the first voyage of the Polar Alaska, strong impacts occurred on the tank walls. The resulting analysis showed that the liquid motions in the tank could become critical when the period of the wave inducing motions of the ship came close to the resonant period of the liquid inside the tank. The resonance period of the liquid in LNG tanks is a function of liquid depth, tank geometry and standard gravity, as shown here below:

$$T = 2\pi \sqrt{\frac{l}{\pi g} \frac{1}{th\left(\frac{\pi h}{l}\right)}}$$

(1)

Where:

- l: tank geometry parameter (tank length in case of longitudinal resonance, tank breadth in case of transverse resonance)

- h: liquid depth
- g: standard gravity

This resonance motion caused the creation of a powerful LNG progressive wave which broke on the vertical bulkheads.

This ultimately produced some slight damage in tank n°1, where the primary insulation space was partially infiltrated by gas. After degassing the tank in question, it was observed that the electrical cable supports of one of the cargo pumps had been torn and that the debris, moving within the liquid, had punctured the primary membrane at some points.[1]

Nearly two years later, her sister ship the Arctic Tokyo went through two successive typhoons (Trix and Virginia) in Tokyo bay during her 29th return voyage, with approximately the same liquid heel in tank #1. This resulted in four localized primary membrane deformations. They were due to box cover indentations just underneath the primary membrane because of strong liquid motions inside this tank. These deformations were localized at a height corresponding to the free surface elevation, and in the corners of the aft bulkhead. One of these deformations led to the failure of a manually welded joint over 15mm in the primary membrane, but due to the high safety offered by the secondary membrane which was intact and perfectly tight, the LNG could still safely remain in tank #1 for four days, until calm sea conditions came back again and liquid was transferred in tank #4 in order to decommission tank #1. These are the only cases in the 40 years' LNG shipping history where sloshing loads have led to a breach of tightness of the primary membrane. And this has to be related to the industrial practice overall quality which was at that time far from where it is nowadays, whether it is for the welding procedures and tools or for Invar® production itself.

As a result of these two unfortunate incidents, the shipowner was advised to divide the liquid heel needed for cooling among all the tanks, and this was how the sloshing problem was thought to have been solved, at least at that time. Nevertheless, after these benign incidents which had brought about some quite unexpected phenomena, several test campaigns using wave simulators were conducted by French ship designers and also by some Japanese and American partners. These simulations were carried out in tanks which were homothetic to those of the ships, made of Plexiglas and loaded with fresh water, at ambient temperature and atmospheric pressure. The results were designed to reproduce the phenomena detected at sea on the ships. They led the classification societies to recommend a drastic reduction of the upper chamfers in the transverse sections of the cargo tanks, inclined at 45 degrees, thus limiting in the ceiling zone the free surface of the liquid cargo. This shape, chosen by the designers purely out of caution, was meant simply to increase the stability of the ship at sea by reducing the effect of internal wave loads in the tanks.

This recommendation of the classification societies was applied by Gaz Transport to the construction of the new generation of ships, even though they were doubtful about the efficiency of this new principle. The upper slopes were reduced from about 9 meters in the previous designs to 3 meters for the new ones (Jean, 1998)

The Larbi Ben M'Hidi incident

Although some twenty membrane-type LNG carriers with capacities ranging from 40,000m^3 to 130,000m^3 were delivered during the seventies, no other sloshing incident was recorded until 1978, some ten years after the *Polar Alaska* incident. This incident occurred on a large capacity ship owned by the El Paso shipping company which made regular voyages between Algeria and the East coast ports of the United States. This vessel, which could ship 129,500m^3 of LNG in five tanks, was the largest of her kind at that time. The incident appeared to have been caused once again by the phenomenon of resonance between the ship's motions and the liquid cargo's own movements. The sea waves were not exceptional in height, but of a long period (the wavelength was close to the total length of the ship), and this particular matching induced longitudinal resonance of the liquid in the tanks. Since the sea was not particularly rough, no crew member expected the strong structural vibrations accompanied by sudden, muffled noise. No loss of tightness was detected in the Invar membranes, so the vessel could still operate safely. Eventually, when the vessel went to her scheduled dry-dock some primary space box covers were found to be slightly indented in the corners of the ceiling in all tanks. The damage was very limited; the total number of damaged boxes was 45 in all tanks together, and the most impacted tanks were tanks n°1, 2 and 3 with respectively 12, 11 and 13 damaged boxes. Only 3 and 6 boxes were damaged in tanks 4 and 5, respectively.

Despite these very limited consequences and the fact that there had been no consequence on the commercial operations of the ship, Gaz Transport main competitors started a negative campaign against the invar-type membrane systems, which led to the immediate launching by Gaz Transport of extensive sloshing studies together with their partners at that time: the US aeronautics and astronautics giant Mc Donnell Douglas, the classification society Bureau Veritas, and the two Japanese shipyards Mitsubishi Heavy Industries and Nippon Kokan Group. Together they created the “Sloshing Club” to study this question in more depth. One of their conclusions was that to better represent the thermodynamic conditions onboard the real tanks, where a boiling liquid is in constant equilibrium with its vapour, performing model tests with water and air at laboratory's ambient temperature was not sufficient. According to them, this main variation could explain the difference between the very weak impacts obtained in the former experiments and the strong impacts recorded onboard the vessel.

At a meeting of the Sloshing Club in London, a working plan was defined for the purpose of measuring the impact pressures generated by the movement of the liquid and the distribution of the impact areas in the tanks. For the simulation model, the use of liquid methane was obviously out of the question, but one alternative was that the water representing the cargo had to be tested in an atmosphere of steam in equilibrium, which could be obtained by creating a partial vacuum in the Plexiglas tank. The experiments conducted under these conditions showed that the impact pressures were much higher than those expected, which could explain the impact heard onboard the ships under actual conditions of operation. Thirty years later, Maillard and Brosset (2009) will show that actually more than the gas pressure above the liquid or the fact that liquid is boiling, this is the correct simulation of the density ratio between liquid and gas which is the main parameter for a more realistic simulation of actual sloshing events.

The observations made on the new test set-up showed as well the advantage of restoring the large slopes in the upper part of the cargo tanks, which somewhat clipped the waves and reduced the turbulence in the liquid. For ships in service having small slopes which could not be modified, Gaz Transport studied and defined a way to reinforce the

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[1] Jean (1998) interestingly mentions that a copper “pancake”, melted and re-solidified, formed by the fusion of the electrical cables, was found on the bottom of the tank, showing that a violent electrical arc had occurred in the tank when the cables were torn, without causing any other damage. This was seen as additional evidence that the system posed no risk of combustion or explosion, in tanks that contained no oxygen.

upper areas of the cargo tanks, especially in the ceiling corners. This solution did not eliminate the impacts due to resonance but prevented any damage which could be observed consequently to these impacts. Nothing was heard about sloshing for the next 20 years or more… (Jean, 1998)

SLOSHING UNDERSTANDING ENHANCEMENT OVER THE LAST DECADE

Improvements in sloshing analysis approach and tools

The sloshing phenomenon came back to the forefront in the late 90's, when the LNG industry started to look into the offshore LNG unit concept once again, taking advantage of both the experience gained from the oil industry in this field and the advances in the available tools required to study these concepts. For example, easily available computing power had increased up to a sufficient level so that numerical tools became a good additional tool to model tests. 3D CFD codes permitted the rapid study of several new tank designs and their effect on liquid motions without relying exclusively on expensive and time-consuming model tests (Spittael et al., 2000, Gavory, 2005 and Gervaise et al., 2009). Some of the phenomena very localized in time and space, involving several physics fields (fluid dynamics, thermodynamics, fluid/structure interaction) still could not be simulated with a satisfying level of precision, but the overall behaviour of the fluids, the liquid and gas velocity vector fields and the hydrodynamic loads proved to be accurately modelled. In parallel, the newly merged Gaztransport and Technigaz company, thanks to the numerous membrane LNG carriers orders in the 90's and the prospect of winning the enviably large markets of Qatari projects (more than 45 potential orders of giant LNG carriers of more than 200,000m^3 capacity each) as well as offshore units, invested heavily in the development of innovative testing tools. This equipment was developed for various objectives:

- Simulate more accurately the ship motions at sea, with six degrees of freedom.

Figure 8: 6 d.o.f. test rig

- Increase the model scale to reduce the uncertainties due to small scale model tests.
- Increase the number of pressure sensors and their density over the given impacted areas.
- Improve the time and space definition of the sloshing impacts, to better understand the physics behind.

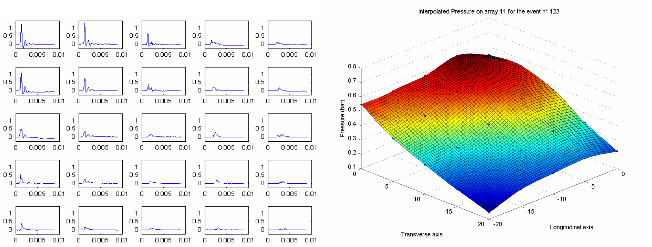

Figure 9: Sloshing impact post-processing in time (left) and space (right)

These technology breakthroughs tremendously improved the knowledge and understanding of these phenomena and led to the design and validation of the largest LNG tanks ever built; more than 50,000m3 cargo capacity each, and of the associated very large LNG carriers, called Q-max, of 266,000m3 cargo capacity.

The Catalunya Spirit incident

If not mastered, sloshing was thought to have been understood deeply enough to envision with great confidence the future development of very ambitious projects such as giant floating natural gas liquefaction plants, and the whole industry was pleased about the way this historic and annoying problem had finally been overcome.

This is why the information coming from Navantia shipyard in El Ferrol, Spain during spring 2006 came as such a shock for all the people who received it. The Catalunya Spirit, a 138,000m3 LNG carrier delivered in 2004 had entered for a schedule routine dry-dock inspection, and due to a malfunctioning cargo pump a decision was taken to open the cargo tanks and inspect the other cargo pumps. Upon entering the tanks it was noticed that the cargo containment system appeared to be damaged in a number of locations and a more detailed inspection was initiated. Investigation revealed that the membrane was indented in tanks 2, 3 and 4, in a zone just above the upper knuckle of the lower chamfer on both sides of the tanks, indicating that the box covers behind the membrane were indented. In some areas, the invar tongue immediately above the indents had been bent upwards and the majority of the most indented areas were located right below the invar tongue. This seems to indicate the existence of a local over-pressure due to the presence of the invar tongue. This was the first real evidence of the strong influence of local effects on the sloshing impact pressures, and some extensive studies were consequently launched on this particular subject.

Figure 10: indented primary membrane (left) and deflected top cover (right)

Another major finding of the investigation was that it threw the whole sloshing analysis methodology back into question, and especially the basic premise that for a given wave period, the greater the ship motions or accelerations, the higher the impact pressures. This was the reason why in the methodology widely accepted and used at this time, only a wave envelop with the highest sea-states over a given return period was studied, and was thought to be representative of the worst possible environmental conditions with respect to sloshing loads (see Gervaise et al., 2009). This proved to be a wrong postulate. The investigation simulated the actual vessel route during the event, and showed that sea-states with an intermediate wave height can, when associated with a critical wave period, lead to much higher sloshing loads than expected, especially at low fillings. This is probably because for such cases, the transverse progressive wave which develops from one tank side to the other breaks directly on the vertical wall, whereas for higher wave heights it will tend to break before reaching the opposite wall, and the fluid impacting this wall will actually be a mixture of liquid and gas, with a lower density and smoother consequences on the containment system. This led to a global overhaul of the methodology (see Gervaise et al., 2009) and a rethinking of the analyzed environmental conditions which permit to validate tank designs and associated containment reinforcements. This has been the last time we heard about sloshing damages on a No-type membrane containment system.

Most recent sloshing evidences on in-service vessels

The Mark-type containment systems (whose common characteristic is the primary corrugated stainless steel membrane) have been spared these sloshing issues from the first days of membrane LNG carriers, mainly because it was thought that the primary membrane corrugations would entrap some gas during the liquid impacts and this entrapped gas would act as a cushion and dramatically reduce the impact pressures. No element ever refuted this hypothesis, which had even been backed up by drop-tests of corrugated stainless steel sheets on liquid nitrogen in the early 90es (see Claude and Rico, 1993, Ha et al., 2005). The fact that several Mark I and Mark III vessels, with overall capacities and tank geometries very similar to those of No-type vessels, have been trading without any sloshing record until last year could be seen as an actual proof of this supposed benefit. Again, the LNG industry was strongly surprised to learn during summer 2008 that within a few months some deformed corrugations of the primary barrier had been observed on a total of three Mark III ships! These damages did not turn into cracks, and there never had been any breach of tightness, so once again the deformations were observed on the occasion of a routine dry-dock inspection, and did not call for immediate service interruption for the concerned vessels.

The deformed membrane corrugations were located in the lower areas and in the upper trihedral areas of some tanks. It is to be noted that not all tanks had deformed corrugations, and more interestingly that the damaged tanks were not the same for the three vessels.

		Nb of deformed corrugations	
Ship	Tank	Portside	Starboard
N1	#1	0	0
N1	#2	461	452
N1	#3	1075	987
N1	#4	32	44
N2	#1	0	16
N3	#1	26	19

Table 1: Number of deformed corrugations in the lower areas of ships N1, N2 and N3

As part of the investigation still in progress at the time of writing, one probably fundamental finding is that the two tanks where the highest number of deformed corrugations has been observed are tanks where the carried liquid heel reached more than 4 meters, whereas in all other tanks and ships, the amount of liquid never reached more than 3 meters. Notwithstanding the different routes and weather conditions these three vessels could have encountered, it seems that the liquid height, especially in this 2 to 5 meter range, plays a major role in sloshing intensity. The load increase curve seems to have a very steep slope in this range, which is illustrated by the factor 10 to 20 between the amount of damaged corrugations between 3m filling level and 4m filling level.

These incidents tend to prove that the cushioning effect which was believed to reduce the sloshing pressures may not have as positive an effect as primarily thought, and that local over-pressures can appear during a liquid impact at the location of the corrugations because of their shape and the non-flatness parameter they introduce.

CONCLUSIONS AND WAY FORWARD

The actual consequence of sloshing impacts on existing LNG carriers demonstrates the real and urgent need within the industry for a better understanding of the full scale sloshing loads on membrane LNG carriers. GTT's continuous involvement and strong will for improvement of the knowledge and of the simulations of this phenomenon, even more emphasized by the recent events, is illustrated by the various avenues of research which are currently investigated, and which will be presented in detail during this coming sloshing symposium. Among them, an extensive development work has been started on the numerical simulation area, whether it is by improving standard approaches or by developing SPH (*smoothed particle hydrodynamics*) models (Braeuning, et al. 2009, and Oger et al. 2009). This should help understand the local behaviour of the fluids (liquid and gas) and structure during a sloshing impact.

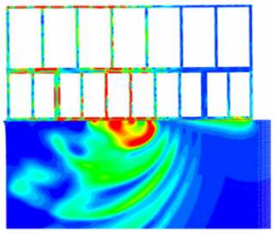

Figure 11: Example of a SPH simulation of a fluid - structure interaction during a liquid impact

Full scale tests have been launched through SLOSHEL JIP (Brosset, Mravak, Kaminski, Collins, Finnigan, 2009) or with strain gauges directly installed in the insulation components of sailing LNG carriers.

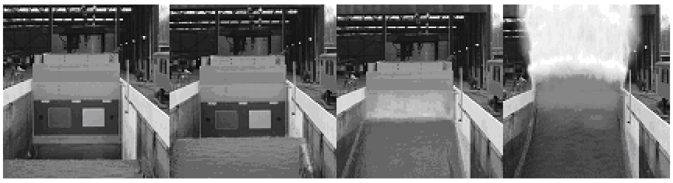

Figure 12: Full scale impacting wave during SLOSHEL JIP

It is worth noting that pressure sensors had already been installed in the tanks of an LNG carrier in 1975, without noticeable results. Furthermore, after her first five voyages, during which no significant pressure had been recorded, the ship was laid up and then scrapped a few years later for economical reasons. Due to the latest incidents and to the rapidly growing fleet, the last few years have seen a renewed interest for a better return of experience and for actual recordings of sloshing loads at sea. This interest materialized in the instrumentation of one of the new generation membrane LNG carriers delivered last year through a Joint Industrial Project involving GTT, some classification societies, the vessel's ship-owner and the shipyard who built it. This vessel is currently operating and some first results of these full scale measurements are expected within the next months. This project may open the door to a new era of systematic sloshing monitoring at sea which would stir up the way this phenomenon is tackled at the moment.

Finally, innovative methods for measuring the important characteristics of the sloshing impacts at model scale and for post-processing the associated recordings are being developed, to permit the study of key parameters such as the influence of liquid and gas density on impact behaviour (Maillard, Brosset, 2009), or to build up reliability-based methods of estimating the loads on the containment system and its resistance to these loads (Gervaise et al., 2009). In the history of LNG transportation at sea, all the incidents have always led to advances in the knowledge of the sloshing phenomenon, in order to maintain the incredibly high safety record of this industry (no major incident or loss of cargo over the last 40 years, for a total fleet of more than 300 LNG carriers). The unfailing implication and relentless efforts of a large number of scientists and engineers, not only in GTT but in the whole marine industry, will undoubtedly help us achieve together this ultimate objective.

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