Propulsion system shaft line analysis of a 70.000 dwt LNG tanker

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Abstract. In the presented project, a study was made on the propulsion installation on board the LNG tanker with a load capacity of 70,000 dwt. In this regard, all the steps regarding the calculation and design of the main elements of this type of installation were followed, such as the propulsion engine, the propeller and the shaft lines. At the end of the shaft sizing stage, a simulation was performed in a specialized software to analyse and verify the evolution of the component elements in an operation scenario.

Keywords. LNG, propulsion, analysis, tanker, simulation.

1. Introduction

In view of the transport of LNG under cryogenic conditions, the structures and physical characteristics of such vessels are strictly laid down in international standards ("Code for the Construction and Equipment of Ships Carrying Liquefied Bulk Gases" and "International Gas Code, abbreviated IGC, Chapter VII SOLAS Convention").

The rules of these basic documents are constantly being reviewed, always with a view to increasing security, being systematically accepted by all classification societies that have incorporated them into their legislation. Security measures require technical solutions for the construction of LNG tankers with extremely low temperature resistant materials, require the use of waterproof pipes and control of the atmosphere in areas close to cargo, require primary and secondary insulation of storage space, definition of hazardous areas for construction of installed electrical equipment and removal of all flammable sources from areas where evaporated LNG could come into contact with air.

In the long run, the same study claims that the LNG shipping market will be greatly influenced by the way energy markets are regulated. Projects that use LNG as a base fuel are very expensive, and the payback period is very long, and this would benefit transport investors, while they are looking for longer-term charter contracts. However, importers are looking for short-term contracts to remain competitive in the energy market, while end-users have more freedom when it comes to choosing their energy source, with more and more people opting recently for energy, renewable energies. At the same time, a study by the giant Shell claims that the LNG market has a development perspective, while it will be increasingly sought after in the field of road transport. The study says that in 2022, the demand for liquefied natural gas (LNG) worldwide will reach 384 million tons, which is fueled by the need to reduce CO2 emissions. Most of the additional demand for liquefied natural gas comes from Europe and Asia, especially China, where consumption increased by 40% in 2020.
compared to the previous year, making it the largest importer in the world. Along with the demand for liquefied natural gas, investments in commercial vehicles powered by liquefied natural gas will increase, as well as in distribution and supply infrastructure. The Shell report states that one of the main users of liquefied natural gas will be heavy transport and predicts that by 2030 in Europe there will be 280,000 commercial vehicles that will use this fuel (compared to 5,500 today and 155 filling stations), while in China there will be 300,000 such vehicles. In 2018, the consumption of liquefied natural gas reached 319 million tons, three times more than in 2000, when only one hundred million tons of liquefied natural gas were burned. According to the same report, in 2019, the demand for LNG will increase by 35 million tons, and in 2022 it will reach 384 million tons. LNG is also advancing in shipping. Currently, 143 ships use liquefied natural gas as their main fuel, while another 135 ships of this type are under construction. [1]

2. LNG tanker technical features

The sea transport of liquefied gases began in the 1920’s, with the transport of the first loads of propane and butane in pressurized tanks, at ambient temperature. By the 1950’s, liquefied gases began to be partially refrigerated and ships to be equipped with low-temperature cargo tanks. Since the 1960’s, fully refrigerated ships have been transporting LPG, LNG and ethylene at atmospheric pressure. At the same time, the transport of ammonia has become a common operation, and the transport of chemical gases such as butadiene has become a common commercial operation.

Gaseous cargoes are transported in a liquefied state, as the liquid occupies a volume 850 times smaller than the volume occupied by the gas, which means that a much larger amount of gas can be transported. If the goods are transported in a pressurized manner at ambient temperature, the cargo vessels must be able to withstand the pressure of the goods at an anticipated temperature as the highest that can be encountered throughout the voyage with the ship loaded. Cargo tanks must also be insulated. The liquid gas in a tank is in pressure equilibrium with its vapors. Each pressure corresponds to a well-defined temperature. Any change in the temperature in the tank produces evaporation (if there is a supply of heat) or condensation (if there is a cooling) until a new equilibrium reappears under a higher or lower pressure, respectively. The temperature-pressure torque is therefore a characteristic parameter of the transport conditions of the product.

Atmospheric temperatures encountered at sea vary between -25 °C and +45 °C. Therefore the reference conditions for gas transport were set at +45 °C for temperature and at an atmosphere (1,013 bar) for pressure. This means that ships must store and transport liquid cargo under these conditions. In particular, ships carrying products whose boiling point at atmospheric pressure is less than +45 °C and shall have two cooling installations capable of keeping the product liquid or having insulation to delay evaporation as much as possible. The mode of transport of liquefied gases is highlighted by the thermodynamic characteristics of the gases.

All liquefied gas carriers have the basic equipment and facilities necessary for the safe handling, storage and transport of specific cargo. The main differences between the types of ships are the measures taken to prevent vaporization and the degree of flexibility of the system in terms of the number of sorts of cargo transported simultaneously. The equipment consists of specific liquid and vapor piping, cargo pumps, gas compressors, heat exchangers and specific equipment for gas detection, remote control of valves, pumps, compressors, etc.

**Cargo operating system** - The operating system of the cargo installations is made for:
- loading / unloading of a type of cargo in/from tanks;
- in the process of cleaning cargo tanks;
- in the process of lowering the temperature of the goods;
- in the process of filling tanks and piping with cargo steam or inert gas.

**Liquid and vapor piping** - Each cargo tank on board an LNG tanker is connected to:
- a liquid cargo loading line, which enters the cargo tank and extends to close to the bottom of the tank to reduce thermal load and which is usually provided with some deflections to prevent
thermal stress. This line connects the liquid lines, is placed at the master torque and allows loading from any board;

- a liquid discharge line;
- a freight steam line;
- a line for unloading cargo steam;
- a spray loading line (sprayed liquid).

Normally a drain valve is mounted on the dome of each tank and connected to a pipe leading directly to the base of the ventilation pipe, thus ensuring a sufficiently large distance from the accommodation spaces. The cargo steam line leads to a cross section of the steam return line on both sides, is located in the area of the master torque and can be used to carry gas vapors to the compressor. Assemblies are often made that allow this line to be connected to the safety valve in the ventilation mast or to a purge pipe used for gas-free operations. As a particular piping is used for several purposes, it is necessary for it to have a high degree of flexibility which consists in particular of interchangeable portions of the piping to insulate the system. This is very important when transporting different types of goods or when performing various operations on the goods. Interchangeable pipes are also used to connect the inert gas system.[2]

![Figure 1: The complexity of a cargo system on board LNG ships](image)

**Cargo pumps** - The cargo pumps are mounted on all ships for unloading operations. On some LNG tankers, cargo can be unloaded by increasing the pressure in the vapor space using compressors, which is an alternative method of unloading cargo from pressurized or semi-refrigerated ships. Most liquid pumps are centrifugal and generally differ in engine layout and drive mode. In the case of LNG tankers, the following three types of pumps are used:

- submersible pumps, which consist of a unitary pump-motor combination mounted inside the cargo tank and supported by the discharge or discharge piping;
- depth pumps, these having the motors mounted at the foot of the discharge pipe, the actuation being made by means of a long shaft which receives the movement from an electric or hydraulic motor which is mounted in a vertical position on the tank dome;
- deck-mounted pumps, they can be electrically or hydraulically operated and can be used both as main pumps and as auxiliary pumps. When used as main pumps, they must be fitted with a priming system to prevent cavitation.

**Cargo steam compressors** - Are mounted on all liquefied gas carriers, their role depending on the type of ship. Centrifugal type compressors are mounted on board LNG carriers, with the role of delivering cargo steam to the engine compartment and intensifying the return of steam to land. On board ethylene or LPG carriers, compressors are used to increase the vapor pressure in the cargo
system, during purge or gas-free operations, to equalize the pressure between ship and land before loading pressurized cargo or to prime cargo pumps mounted on deck. Compressors are also used in the reliquary plant to increase the pressure and temperature of vapors before condensation. The compressors are actuated by means of traction shafts which penetrate the bulkhead through special holes provided with sealing systems. The ventilation equipment in the compressor chamber is often interlocked with them to ensure that their space is ventilated for some time before starting the compressors.[3]

**Heat exchangers** - Ships often have heat exchangers in the form of condensers or evaporators so that cargo steam can be liquefied and liquid cargo can be vaporized. Liquid cargo vaporizers can be used during purging and, together with booster (auxiliary) pumps, are used to allow fully refrigerated cargo to be unloaded into a pressurized storage tank unsuitable for low temperatures. LNG carriers typically do not have a relaying facility, and steam discharged from the cargo hold is captured and burned in the ship's engines or boilers. The use of steam for this purpose may be restricted to coastal vessels, where maneuvers are very common.

**Cargo steam combustion plant** - The boil-off gas combustion system (which are the vapors resulting from the evaporation of natural gas from cargo tanks) is essential for transporting LNG tankers. This type of installation contributes to saving fuel during the trip, but also to reducing the evaporation level of the liquefied natural gas transported. The generation of BOG type gas (boil-off gas) takes place in any mode of operation of the LNG type ship, but also at the level of the terminals from where the cargo is loaded. Boil-off gases are largely generated by the fact that natural gas is stored in a cryogenic state in an environment in which it is much warmer than in the compartments in which it is stored. The LNG gas tanker "Maran Gas Apollonia" has the following units for managing the vapors generated by the variation of the temperature of the cargo on board, among which the most important are:

- The low-pressure compression system in the gaseous fuel supply system of the main engine, which is also the subject of this diploma thesis;
- High pressure compression of natural gas for return to the cargo piping system;
- The BOG reliquary system within the tanks and the return to the storage tanks;
- Low pressure compression through a BOG capacitor, which allows recondensation and conversion back to LNG.

The LNG tanker “Maran Gas Apollonia” is the eleventh ship built for the “Maran Gas” transportation company. It was ordered in 2012 and was operationalized and launched on June 1, 2014. Being built at the “Daewoo SB & ME Co.” Shipyard in Okpo-dong, South Korea, the ship has all the equipment of a modern ship. From the point of view of the classification of LNG tankers, it belongs to the category of fully refrigerated tanks.
Figure 2: “Maran Gas Apollonia”, the 70000 dwt LNG tanker

The technical characteristics of the ship are:
- IMO number: 9633422;
- Call sign: SVBV2;
- MMSI: 241275000;
- Gross tonnage: 85773;
- TDW: 70434;
- Ship type: Fully refrigerated LNG tank;
- Year of construction: 2014;
- Flag: Greece;
- Construction length: 294.2 meters;
- L between perpendicular: 289 meters;
- Maximum width: 46 meters;
- Construction: Daewoo SB & ME Co., KOR;
- Type of cargo tanks: Pressurized tanks with membranes.

Figure 3: Arrangement of cargo tanks on board the ship
3. “Maran Gas Apollonia” LNG tanker propulsion system

A determining factor for the propulsion of LNG dolovs is the safety system specific to that vessel. There are two projects initially developed for the construction and safe storage system on board LNG tankers: the “Moss Rosenberg” design and the membrane storage tank system which provides for the use of membranes supported on the insulated keel structure. The first model was first implemented in 1971 and is known for its independent spherical tanks that usually have the upper part uncovered on the main deck. The storage system in membrane tanks is the most used, being developed by the company Gaztransport” and, later by “Technigaz”, being also called the GTT system. The GTT system has been continuously developed and currently allows the level of boil-off (gas loss resulting from the temperature difference in cargo tanks and the external environment) to be reduced to 0.08%. Among these systems, newly built ships are increasingly adopting the “Mark III Flex” and “Mark V” models. A new membrane system, KC-1, has recently been developed by KOGAS. It is currently installed aboard two LNG tankers. At the level of 2017, 74% of the active ships in the world fleet had GTT systems and only 26% of the “Moss” system. This model is also preferred in the case of 91% of ships in the register of orders to be built.[4]

In order to maintain the pressure in the cargo tanks under normal atmospheric conditions, in the case of both storage systems, the BOG (boill-off gas) must be extracted from the tanks and subsequently used to power the main engine. This principle has long been used to power engines or turbines, being a reliable concept, but not really optimal. Since the early 2000’s, these propulsion systems have been specially improved and innovated to reduce the cost of fuel. Since 2000, the bunkering price of naval fuels has risen steadily. In an attempt to combine low fuel consumption with the need to use BOG, a number of approaches have been developed, depending on the specific concept of transport (ship load capacity, ship speed, voyage time, etc.). Any comparison of alternative LNG ship propulsion concepts must take into account the overall complexity of the LNG transport concept. Nowadays, LNG carriers have a wide variety at their disposal when it comes to choosing the propulsion system.[5]

Following the presentation, the optimal parameters of the main engine-propeller system is set as the following:
- Engine power (at 90% MCR): 13,769 kW;
- Propeller speed: 90 rpm;
- Cruise speed range: 15 - 20 knots.

In the maritime industry, both shipbuilding and propeller manufacturers offer products that fall into ranges that have incremental characteristics. Therefore, based on the information of the above presentation, the engines with the characteristics closest to the necessary ones will be chosen, in order to achieve a construction with functional parameters as close as possible to the optimal ones. Thus, from the MAN B&W company a two-stroke engine, of dual fuel type, from the MAN ME-GI series having the essential characteristics presented above.

The presented engine develops the required power (13,769 kW) at 90% M.C.R. and at a speed of about 90 rpm. It is immediately noticeable that the characteristic parameters of the adopted engine are very close to the previously calculated optimal parameters (the calculated running speed is even higher than initially intended and the relatively high percentage of M.C.R. does not seem to be a rarity in the context of more recent achievements). Therefore, by reducing the speed, speed and percentage of the M.C.R. they will be within the desired limits, so no further adjustments or optimizations are needed at this stage.

In addition, the MAN ME-GI series engines also have the ability to run on gas. Thus, instead of burning and eliminating gas vapors resulting from the phenomenon of evaporation and temperature variations (BOG), they are directed to power the main engine, significantly reducing the costs of fuel consumption, but also the costs of losing a certain quantities of the cargo transported. The ME-GI engine is equipped with an additional high-pressure injection system that allows the introduction of gas vapors into the combustion chamber. It is ignited by a quantity of pilot fuel, facilitating continuous operation on the gas.
4. Propulsion system shaft line analysis

FEM (Finite Element Method), starts from the idea that for the analysis of the deformation of a continuous structure (with some geometry and complex boundary conditions) the exact values of the parameters (displacements, forces) cannot be calculated or if they can be the calculation effort would be unjustified. If an approximate solution is possible, easier to perform, and the degree of approximation is, engineered, reasonable this solution is accepted as a solution for the initial structure. In other words, the analysis with FEM of a structure implies its replacement with another for which the calculation of the parameters is easier to perform, the values of the parameters being approximate for the structure to be analyzed, but acceptable from an engineering point of view. FEM, for the case of structures, can be seen as the extension of the classical matrix statics method (developed for the
study of assemblies with one-dimensional structural elements, bar structures) to two-dimensional and three-dimensional continuous structures.[6]

MEF involves a process for discretizing (natural and/or artificial) the analyzed structures and a specific way of establishing the equilibrium matrix equation (usually using a direct formulation) for each finite element (in the form of a system of algebraic equations). The finite element of the discrete model must be compatible with the development in space of the structure and the mathematical model that defines it to simulate, as well as possible, the behavior of the structure in the area it covers; thus, if the structure has a unidirectional development the corresponding finite elements are one-dimensional (1D), straight or curved, in the case of a flat development the corresponding finite elements are two-dimensional (2D), with straight or curved sides, and in the case of a spatial developments the corresponding finite elements to be three-dimensional (3D), with flat or curved faces.

For the study, the shaft line of the reference ship with an established total length of 15 m will be analyzed, and the inner diameter is $D_{\text{int}} = 0.4 \cdot D_{\text{ext}}$. The construction of the shaft will be simple, without flanges. In this sense, the shaft model will be generated in the Ansys program, a program specialized in the finite element method. Next, the following operating scenarios will be analyzed: operating the engine at maximum power and locking the propeller in cases such as landing on a sandbank and the normal operating mode of the propulsion system when the ship is moving at a maximum speed of $15 \text{N} d$, a speed corresponding to the maximum power of the propulsion engine and a pushing force which is considered to be at maximum value.

In the simulation process, the first step is to establish the system of units of measurement for the precise determination of shaft line parameters. Next, the geometric parameters of the shaft line are introduced, such as the length along the X, Y, Z axis, volume, mass, value of the scaling factor, number of bodies, number of active bodies and the type of analysis is chosen, in this case being a three-dimensional analysis. After completing these steps, ANSYS is used to automatically generate the geometric model of the shaft:

![Figure 6: Generating the shaft geometric model][7]

The next step in the simulation is to define the coordinate system, then you can set the parameters for generating the discretized mode of the shaft, following the generation of this model:
Figure 7: Performing shaft discretization using square finite elements [7]

The analyzes can then be performed on the defined and discretized model of the shaft. As in the previous steps, a series of parameters are redefined and then loads related to the motor torque are applied:
Figure 8: Applying loads related to the motor torque on the shaft [7]

The specified torque given by the engine depends on the parameters for the analysis of total, directional, stress deformations are defined below, as shown in the figures below:

| Object Name | Total Deformation | Directional Deformation | Equivalent Elastic Strain | Equivalent Stress | Strain Energy |
|-------------|-------------------|-------------------------|---------------------------|------------------|--------------|
| Scope       | Solved            |                         |                           |                  |              |
| Scoping Method | Geometry Selection |                         |                           |                  |              |
| Geometry    | All Bodies        |                         |                           |                  |              |
| Type        |                   |                         |                           |                  |              |
| By          | Time              |                         |                           |                  |              |
| Display Time | Last              |                         |                           |                  |              |
| Calculate Time | Yes              |                         |                           |                  |              |
| History     |                   |                         |                           |                  |              |
| Identifier  |                   |                         |                           |                  |              |
| Suppressed  | No                |                         |                           |                  |              |
| Orientation | X Axis            |                         |                           |                  |              |
| Coordinate System | Global Coordinate System |                         |                           |                  |              |
| Results     | Minimum 0. mm     | -6.4269 mm               | 6.4773e-005 mm/mm         | 9.256 MPa        | 1977.1 mJ    |
|             | Maximum 9.43 mm   | 9.4267 mm                | 6.4371e-004 mm/mm         | 128.31 MPa       | 42016 mJ     |
| Information | Time 1. s         |                         |                           |                  |              |
| Load Step   | 1                 |                         |                           |                  |              |
| Substep     | 1                 |                         |                           |                  |              |
| Iteration Number | 1               |                         |                           |                  |              |
| Integration Point Results | Averaged |                         |                           |                  |              |
Figure 9: Diagram of total deformations expressed in [mm] [7]

Figure 10: Diagram of directional deformations along the X axis expressed in [mm] [7]
Figure 11: Diagram of equivalent elastic stresses expressed in [mm/mm] [7]

Figure 12: Von-Mises equivalent voltage diagram expressed in [MPa] [7]
5. Conclusions
At the end of the analysis the program automatically generates a series of tables in which data are presented regarding the qualities of the material from which the shaft line is produced and how it behaves during the simulation.

Following the analysis of the diagrams presented in the previous chapter, it can be concluded that the maximum displacement of the propeller shaft is 9.4267 mm, and the maximum value calculated for the shaft efforts is 0.00064371 mm/mm. Furthermore, the maximum value of equivalent voltages is $0.12831 \cdot 10^8$ Pa, while the voltage energy is $42.016 \cdot 10^3$ mJ. All of the above lead to the final conclusion that, although the most unfavorable loading situation has been taken into account, a little exaggerated in some places, the shaft is still close to the specified yield strength. This demonstrates that the calculation of shaft liners is correct, and safe, as long as their dimensions are not oversized.

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