

LARGE INDUSTRIAL TURBINES FOR FLOATING APPLICATIONS

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1 Introduction/Background

For large floating LNG or gas-to-power applications a large offshore power supply is needed. To access economies of scale, large industrial turbines can offer advantages in terms of cost and footprint per installed MW.

GE's industrial gas turbine line was evaluated in a joint scoping study. A solution based on the Frame 9E Gas Turbine was studied and shown to be an option that achieves a high power density per footprint area.

The study addressed layout, package, mounting, maintenance, and included:

- Analysis of foundation-base plates dynamic stiffness and related effects on rotor critical speeds
- Evaluation of the core, flange-to-flange engine in a motion environment
- Operability and Maintainability assessment.

The basis for the study is a power system consisting of 5 units, where one is an idle spare.

A concept of lateral engine removal with hydraulic alignment of the GT package was also included, cutting the maintenance downtime to roughly half the time of conventional on site maintenance procedures. The study concluded that a floating Frame 9E Gas Turbine could be developed for an attractive range of offshore applications.

2 Objectives of the paper

The study is based on several tasks, all of them addressing the constraints given by the peculiarity of the floating application: footprint limitation, pitch-roll-yaw and accelerations dictated by the sea motion, maintenance philosophy based on ease of accessibility, installation on a three-point baseplate with finite stiffness and modular replacement.

3 Development/Methods

a. GA definition

The width of the vessel was given as a constraint. GEO&G and EM worked together and determined that it was advantageous to group the units in sets of two so that they could share maintenance spaces. This set of two units is referred to as a "super module" in this report. The gas turbine shaft line is parallel to the centerline (bow to stern) of the ship. This alignment is typically preferred based on the fact that the roll of the vessel is larger than the pitch. The size constraint for the "super module," containing two GTGs plus the maintenance area, is 30 by 35 meters. The space constraint drove the design to a multi level arrangement with GT exhaust duct inlet duct and generator sitting on a main baseplate supported by three gimbals. The main baseplate is limited to 27.1 m in length for easy manufacturing and transportation still able to comply with application constraint. This length limitation required the removal of the typical starting motor skid from the front of the gas turbine. The use of the generator for starting was chosen as the preferred configuration. An off base enclosure around the main baseplate with a footprint of 27.1 by 10 meters does not contain any auxiliary system except the DLN skid in case a DLN solution will be chosen. The chosen design encloses both the gas turbine and the generator compartment, since a single three-point baseplate was required. It was considered infeasible to have an enclosure surrounding only the gas turbine and effectively seal between the baseplate and the deck. Thermal expansion would make the design of such a system very challenging. This decision drives the large requirement of the water mist fire suppression system. Inlet and exhaust duct will be vertical to fit in the space limitations. The typical configuration requires a side mounted and separately supported exhaust duct; this is an innovative configuration that has never been installed. As a side benefit this solution also leaves the most possible space laterally to facilitate maintenance operations limiting the amount of work.

A second deck at level of approximately 20 meter will hold the exhaust with its transition piece and part of the ventilation system. This solution gives about 10 meter space from the top of the enclosure to accommodate ventilation ducts exhaust blowers and bridge cranes for maintenance (see last chapter for

maintenance details). There is some flexibility in the exact height requirement. Oil tanks, one per each train, with oil mist eliminator skid mounted on the top will be positioned underneath the filter houses whereas fire-fighting skid, one per each GTG, will sit together between the filter houses of each "super module". Based on space and maintenance limitations, a plate/frame lube oil cooler is recommended instead of the typical shell-in-tube design.

Fuel gas treating skids, including a coalescing/filter, are located outside the super module and can be designed one per unit or combined, depending on the expected impact on availability. Overall the general arrangement has been designed to allow maintenance by engine lateral removal finding clever solutions to minimize the amount of work and maximize the GT operating time. All the auxiliary skids have been considered leaving out only the fuel-conditioning skid and the control room, which are to be placed by the vessel designer.

Footprint has been squeezed as much as possible to increase maintenance space and reduce the enclosure volume granting the fire fighting system a proper efficiency.

b. Modular replacement system

One of the main targets of this study was to consider a modular replacement, similar to what is used for aero derivative gas turbines, which allows the user to remove and replace the gas turbine without usage of heavy cranes.

Such a solution should minimize the maintenance time, lay down area, support structures, as well as optimize the GT running time (minimizing the downtime). Two methods for removing the gas turbine were considering including: A) removal of the flange-to-flange engine only using a crane and B) horizontal removal of the engine and baseplate. Option B) is recommended based on the fact that the base plate can be easily maneuvered and placed on a cart, while option A) requires the use of a crane and a separate cradle. The complication introduced by option B) is that baseplate alignment is required after each removal. This is typically done only during the initial installation and can take more than two weeks to complete. As a result, GEO&G proposed a solution using hydraulic jacks to reduce the time needed for alignment. Traditional, in-place maintenance is also feasible, but will require some modifications to the lifting arrangement exhaust diffuser and inlet duct. The baseplate anchored to the barge deck by three gimbals will be equipped with 4 hydraulic jacks placed underneath the GT module. These jacks will be used to lift the baseplate onto temporary rails, which will slide the baseplate onto a specially designed cart. Jacks of this size are commonly used in bridge construction. Two sliding pads bolted on the GT baseplate will be used to shift the GT out of the main baseplate through a stepwise motion. It is critical to consider the stiffness of the structural support under the rails and ensure that the resulting deflection is within a safe range as the center of gravity moves from the three-point mount to the cart.

In order to reduce risks of failure these pads will not make use of any rolling item and a special low friction material will be used instead. Pads design has been carried out considering barge motion thus able to prevent any GT uncontrolled displacement and guarantee safe operation.

Additionally 6 extra hydraulic cylinders will control the GT horizontal position through a PLC system guiding the GT alignment after a new unit will be put in place.

Off-base enclosure walls will be removed prior to the horizontal extraction of the engine and baseplate. It is assumed that the general use cranes aboard the vessel will perform this function. No restriction have been given in terms of maximum height of the structure to be likely needed in order to hold inlet and exhaust ducts.

Solution for GT maintenance can be both in place and in a separate shop. For the modular replacement concept, Option B), the maintenance can take place on a dedicated shop aboard the vessel or it can be transported via a separate ship to an onshore maintenance facility. GE deems it feasible to complete all major overhaul-related maintenance onboard the ship despite the motion.

In order to minimize the down time the best solution is the replacement of the GT with a second one limiting the operation to just piping and electrical disconnection (option B)). A spare engine and baseplate should be purchased to maximize availability.

Looking at option B) we see the advantage of a reduced weight and limited dimensions, with the slight disadvantage of the increase of complexity in the removal operations due to the amount of electrical and mechanical connections compared to the removal of the engine only (option A)).

For option A) huge cranes and related structures spanning large distances are needed to transfer the engine onto the car, additional special tools would be required to shift the exhaust plenum and leave space for cranes to be mounted.

As anticipated the intention is not to use lifting cranes during these phases and the replacement of the unit must therefore be done through a horizontal side motion relying on a structure able to support the GT engine preventing it from damage.

The use of a crane for engine removal as in option A would require a temporary baseplate mounted between the GT baseplate and the core engine, this requires the redesign of the original GT baseplate and major changes on hydraulic and mechanical connections.

Option B) has the advantage that the entire FR9 GT module as it is currently designed will be shifted in and out the main three point supported baseplate. Such option will reduce the number of mechanical and electrical connections to be taken apart for the module to be taken out the train.

The module will consist of the GT core engine, GT baseplate, piping and electrical package and inlet plenum. More strict tolerances may be required in the manufacturing of the baseplate to ensure interchangeability between baseplates and quick reinstallation.

c. Maintenance Philosophy

The object of this study was to identify potential approaches and recommend a methodology for maintaining Frame 9E GTGs offshore. The proposed method is aimed to minimize time required for the operation and to enhance safety of the personnel.

Instead of performing a traditional major inspection on-board the barge, a turbine skid (and turbine module) replacement has been proposed using hydraulic systems for handling.

Considering the area available for the operation, the skid replacement is a better solution than the turbine replacement alone. Furthermore, the turbine module replacement calls for the use of cranes that leads to installation and safety problems on board the barge.

The final recommendation for the maintenance method has been made after evaluation of three different kinds of maintenance methods that could have been implemented.

The three possibilities were:

1. Standard Major Inspection, 44 days in double shift requiring lifting operation with bridge crane (70tons) and temporary storage of casing components outside the module.
2. Engine removal by bridge crane, 18 days in double shift requiring a dedicated double bridge crane of 100tons (each cranes) and a smaller bridge crane of 20 tons for HGPI and turbine accessories maintenance.
3. Frame 9E +Skid lateral removal by rails, 20 days in double shift. Consisting in the removal of all the hardware to get access on engine (inlet and exhaust duct parts, ventilation system, enclosure etc), removal and following replacement of the engine with a new one in order to minimize the shutdown. The maintenance of the removed module will be executed in a dedicated workshop (on board) without impacting on production. This operation requires the turbine skid removal with dedicated rails and hydraulic systems.

Standard Major Inspection and Frame 9E Engine removal by bridge crane solutions was not considered optimal due to the large time requirement and lay down area (600 m² per unit), although it is feasible if those limitations are acceptable.

The second case was eliminated mainly due to the high risks associated to pitch & roll motion that can occur during lifting; the engine removal with bridge crane requires a huge engineering/construction effort to realize the bridge crane requirements. It was anticipated that the crane would have to span the entire super module (40 m) while having a lifting capability greater than 200 tons.

The third option (Frame 9E +Skid lateral removal by rails) is a good compromise with respect to maintenance time, safety and area required.

d. Gimbal Design

A common base plate holding the GT and generator will be iso-statically connected to the barge deck through three spherical bearings.

Spherical joints (gimbals) will be required to guarantee a deck connection free from deformations induced from local deck deflections, they constrain two directions whereas all rotation and one displacement will be free.

A finite element model of the gimbals has been made using shell elements in order to gather the local bending stress at weld they might be subjected during extreme conditions.

Gimbals upper and lower plates are constrained using rigid connections to a reference point in order to simulate the bolt junction.

Gimbal stiffness has also been determined to later couple their elastic characteristics to the baseplate in order to evaluate the overall GT structure static and dynamic response.

e. Baseplate Static Analysis

In order to decouple any local barge deformation from the GTG alignment, off shore application requires a definition of an isostatic baseplate connection. This type of a baseplate is commonly referred to as a three-point mount and is widely used for aero derivative gas turbine compressor and generator trains. In addition to the connection stress deployments and stiffness evaluation we also need to comply with appropriate baseplate deformation and stress distribution.

The three-point mount will be a single lift type carrying all the main components (GT, Generator and Exhaust plenum) during the initial installation on the vessel. A finite element model of the three-point mount plus GT baseplate has been made for this purpose, connection point between the three-point mount and the deck

was modeled as rigid link in order to avoid introduction of a level of detail that is not necessary for the feasibility study.

Generator and GT are coupled to the baseplate through undeformable connections as if the casing was infinitely rigid with two reference points at the generator bearings and two at the GT legs to casing junction.

A beam element model was used for this portion of the study, which is able to capture the main baseplate deformations leaving the needs of a more detailed geometrical description and shell mesh model for the detail design phase. Lifting procedure and operation under extreme conditions will be examined. Assuming a baseplate shape with side beams 1.4 meter high made of S355JR steel the study confirms that the structure is safe in terms of stress (axial, bending and shear) and maximum displacement.

f. Baseplate Modal & Harmonic Analysis

A finite element model of the three points supported baseplate plus GT baseplate has been made, connection points and gimbals connection plate have been modeled as rigid link. The model originally made of beam elements was extended with the usage of shell elements in order to capture a more appropriate response in terms of dynamic behavior.

The generator is coupled to the baseplate through undeformable connections as if its casing was infinitely rigid therefore two linked reference points have been placed at the generator bearings. For the GT casing and supporting legs flexibility were computed separately and accounted for the overall response (lateral Analysis). In such a way two separate reference points were used representing shear-plate and legs location. Gimbals and barge deck stiffness are combined in an equivalent value obtained as equivalent from spring series

The modal analysis was necessary to perform the harmonic ones. For the modal analysis the investigated frequencies range was 0Hz to 60Hz, the whole number of the extracted modes for the specified range was 63, and only 11 of the first 12 modes have more than 3% of mass participation factor. Mass participation factor is an indicator of the amount of total mass that will participate to the given eigenmode. The 3% limit comes from GE Oi&Gas internal standards. Four different harmonic analyses have been performed, for all the cases the exciting force modulus was 1N and direction was vertical while the force application location was progressively moved from reference node 1 to reference node 4. The harmonic analyses were necessary in order to identify for each reference node the most significant peak of the direct term response closer to the operating speed so that their stiffness and dumping characteristics could be used to perform train lateral analysis.

No relevant peaks around the operative frequency (50Hz) have been detected.

g. Ventilation System

The primary objectives are to assure:

1. Removal of heat released within package by Gas turbine GE FR9E, generator and all accessories, in order to not overtake temperature limits, in the worst condition, that generally is at maximum site ambient temperature.
2. Flow "quality", in order to limit/avoid:
 - a. Stagnant (low velocity) zones where potential risk of gas leak could be present.
 - b. Unacceptable spread in terms of air velocity and related heat transfer conditions around the GT, especially around the compressor casing.

The general arrangement considered in the FR9 feasibility study is an "off base" enclosure type that encloses the entire three-point mount. After a conceptual design phase, wherein many cases of inlets/outlets layout have been considered, a final configuration has been identified.

The ventilation system is a 2 fans, "pressurized" type, "1X100%" running condition. This means that only one fan (the "main") is active at time, the other (the "auxiliary", but identical to the first) being available for emergency or during the maintenance of the main one.

Design criteria about the ventilation system are satisfied:

- Correct size of ventilation ducting is ensured for each branch, in order to get sufficient heat removal capability (GT enclosure, generator enclosure, load compartment) and flow splitting (in particular equal flow split between openings in the GT Compartment).
- Pressure values inside Generator and GT compartment are acceptable in terms of enclosure strength, with a significant differential pressure between Generator & GT compartments, in order to avoid gas leak from GT to generator compartment.
- Air velocity in ventilation ducts and enclosure inlets/outlets within the acceptable range (< 15 m/s).
- The air temperature is below 80C at the outlet (design limit) and inside almost all the domain. Local zones inside the enclosure that exceed 80 C are acceptable to GE.
- Sufficiently high values of air velocity are present almost everywhere in the GT compartment, where a potential risk of gas leak can occur.
- Acceptable spread in terms of heat transfer conditions around the compressor GT casing.

h. Torsional Analysis

The following report regards the Torsional Analysis of the full train configuration: gas turbine, load coupling and generator. The objective of this analysis is to assure a reliable operation under various operating conditions. The principal aspects covered on this report are the required separation margin for calculated torsional resonances and the required electrical fault torque and torsional response analyses. The conclusions for this analysis are the following:

- All torsional natural frequencies are outside GE design practice exclusion range
- Torsional stresses for major and minor transients meet GE design practice limits
- Adapter could be redesigned to have a larger diameter (same as load coupling)

The full train rotor model was developed based on generator rotor design, GT rotor and load coupling design. Running the simulation with GE Simulation Software, the principal torsional frequencies were detected and compared with the designed separation margin from the main electrical excitations. In addition, the rotor system was analyzed in order to confirm the capability to operate reliably even when excited by transient fault torque events.

i. Alignment Study

The alignment study has the purpose to determine an acceptable alignment under transient and normal operating condition so that the bending stresses and the load on the bearing is within the acceptable limits. The loads on the bearings under “cold” and “hot” condition have been considered in order to optimize the train alignment.

The analysis confirm the following results:

- Bearing loads meet GE specifications for GT and Generator supplier specifications for generator bearings;
- Alignment is acceptable based on the baseplate thermal growths;

Once defined the full train rotor model and the bearing type and features, the analysis were performed to optimize the bearing load under transient and normal operating condition. The bearing loads were calculated defining the elevation of the bearing and keeping into account the baseplate stiffness and thermal growth.

j. Lateral Analysis

Purpose of the lateral analysis of the full train is to determine the critical frequencies, since this will be the first application requiring a Frame 9E to be installed on a baseplate with a finite stiffness. The analysis was carried out comparing the solid foundation with the 3-point base plate installation. The 3 points base plate was modeled on the lateral analysis software using a single degree of freedom mass-spring. Unbalance response analysis was performed to evaluate the vibration level associated with a defined unbalance in steady state and transient condition. A detailed modeling and study was carried out also for Crank speed condition.

The conclusions are the following:

- The lateral analysis can be considered acceptable for the studied application
- No significant variation on vibration level comparing Concrete foundation Vs. 3 point base plate
- Vibration level associated with unbalance distribution is within the Design Practices limits
- Based on GE experience, the vibration level on bearing number one is not an issue
- E class experienced low vibration level on the field (~ 500 units installed)
- GT rotor max unbalance allowed during manufacturing assembly phase is 4 times less than that used for unbalance response (4W/N Vs 16W/N used on the study as per API std)
- For the Crank speed the Oil film property has been calculated at 600 rpm
- Crank speed for Fr9E can be set a different speed lower than 600 rpm (e.g. 450 rpm). Oil film property does not vary significantly compared to 600 rpm
- For Crank speed the vibration level associated with unbalance distribution is within the Design Practices limits

- The lateral analysis performed at low speed can be considered acceptable for the studied application

Given the Train configuration, bearing features, performance and project requirement the lateral frequencies of the train were calculated. The 1st analysis was performed assuming concrete foundation while the 2nd analysis was/ performed considering the bargebaseplate influence.

The vibration levels associated with an unbalance distributions were computed and compared against the acceptable vibration levels for the operating and transient speeds.

The same concept and approach was used to study the operation at crank speed.

k. Rotor Casing Clearance Analysis

Aim of this study is to verify the rotor-casing clearance with the 3 points baseplate configuration in floating environment. The clearance status was analyzed in different operation conditions in order to investigate the worst scenarios.

The conclusions of the study can be summarized as following:

- No significant variation between "Concrete Foundation" and "Baseplate" configuration;
- Top of acceleration ramp Clearance margin greater than 95% for both configuration;
- Even during fired shut down the clearance margin greater than 95%;
- No concerns on clearance regarding acceleration due to sea motion: Clearance margin can allow variation on film oil thickness due to sea acceleration;
- Accelerations due to sea motion do not create rotor deflection and therefore no concerns about clearance;
- The Clearance Analysis results based on the unbalance response can be considered acceptable;

The clearance analysis was based on the vibration level obtained on the "Lateral Analysis Unbalanced Response". Rotor deflection resulting from the sea-motion induced acceleration (< 0.5 g) is very minimal at these conditions and can be ignored for the evaluation of casing clearances. The peak-to-peak vibration values were compared with the clearance considering the worst scenario cases for both "Concrete Foundation" and "3 Points Baseplate" configuration.

The max acceleration was considered based on the bearing load limits.

I. Bearing Loads Analysis

Scope of the study is to determine the additional loads at the bearings generated by the motion of the floating barge and to determine the limiting conditions.

In this analysis the vertical acceleration required to achieve the maximum specific continuous pressure on the bearing was calculated.

The conclusions of the study are the following:

- During normal condition the max acceleration due to sea waves is lower than max vertical acceleration allowable;
- Even doubling the acceleration during normal condition the values are within the limits;
- The most conservative motion case studied would exceed the load limitation on bearing 3, however it is required that under these conditions the rotor should be locked.

The study was based on a given sea motion acceleration and on the bearing load generated by the alignment.

The given acceleration values, were doubled in order to evaluate a worst possible scenario.

The following assumptions were considered for the study:

- Floating barge motion was considered as harmonic;
- Loads treated as "static" since the low frequency (0.05 to 0.20 Hz) of the sea motion;
- Barge's motion loads were added directly to the normal operating loads.

The margin on the bearing max allowable load was calculated based on the bearing load generated during the alignment phase.

The max vertical acceleration was calculated as the maximum acceleration that generates the maximum specific static pressure on the bearings. Finally the acceleration values were compared with the given value. Bearing metal temp and oil drainage are monitored and the alarm is set to protect the unit

m. Oil Drainage Analysis

Scope of this work is to verify the lube system drainage capability in offshore condition and evaluate the risk of flooding or not oil returning to reservoir due to excessive inclination.

Were analyzed also the oil evacuation inside the bearing houses.

The first part of the study was finalized to verify the performance of the system when subjected to motions resulting from a generic sea state as provided by EM. The second part of the study was based on determine the max allowable heave with the following criteria:

- The min design slope for a pipe is 2.5%;

Whether or not the condition of 2.5% design slope is achieved, the oil level on the pipe shall not be greater than half-filled;

These motions were based on the sample barge motion amplitude given by EM. The oil supply pipe and the return pipe are assembled coaxially. For this reason the calculation on the return oil pipe were performed considering an equivalent pipe with a reduced area. No calculation needed for the supply pipe, since this is a pressurized pipe and it is not affected by GT motion. To verify the max capability of the drainage oil system was calculated the maximum slope to create oil level into the pipe equal to "Half-full pipe".

The slope required to have the "half-full pipe" condition was calculated by defining the pipe size, the oil viscosity and considering the actual bearing oil flow.

The conclusions are the following:

- The oil drainage system will likely require modifications for adequate operations over a range of realistic sea states.
- The oil drain pipe on the exhaust side can ensure a drainage up to 1,25° of heave;
- The oil drain pipe on the central bearing must be redesigned. With the new design considered, the max heave can be up to 5.28°;
- The oil drain pipe on the inlet side present a slope of 45°, therefore no risk of flooding.
- The bearing #1 (Inlet side) has an oil discharge pipe slope of 17°, no risk of flooding;
- The bearing #2 (central position) has a vertical oil discharge pipe, therefore no risk of flooding;
- For the bearing #3 (exhaust side) there is an initial vertical discharge channel on the bearing, so that the limitation on heave is due to the drain pipe connected on the bearing.
- Drain boxes height was calculated.

n. Exhaust Plenum Modification

The Exhaust Plenum has been re-designed to allow a lateral replacement of the Engine during a major shut down. The solution proposed is to introducing additional flanges to split the front and rear panels.

The scope of this analysis was to check the plenum behaviour on vibration and thermomechanics loads. The Analysed cases studied are:

- 1st Case –Modal Analysis.
- 2nd Case –Static Thermo-Mechanical Analysis.

The conclusions of the study are the following:

- The modified areas do not show any particular stress;
- Thermal Analysis: The overall stress is lower than Yield stress and no particular stress on the modified areas;

Modal Analysis: The modified plenum design does not affect significantly the modal behaviour.

o. Electric Generator - Starting Motor - Low Speed Motor for Ratcheting

The requirement for a compact design of the train and the idea to have GT, exhaust duct, inlet duct, and generator sitting on a main baseplate, drove the design to the removal of the auxiliary baseplate and consequently the electric motor starting system. More specifically, the limitation on the length of the three-point mount induced by the space constraint required that the typical starting motor system be removed.

This meant that the Electric Generator had additionally to function as Starting Motor and also Low Speed motor for ratcheting purpose. An emergency manual ratcheting system will also be in place, but was not designed as part of this study.

The object of the study was to define the general single line diagram, voltage levels, and to select a proper Generator and Starting system LCI to be used for this purpose.

As a result of the study we found that the generator selected is able to perform the abovementioned functions.

p. Operability Analysis in Island Mode

The general purpose of this study is to understand the capability of the Frame 9E Gas Turbine operating in Island mode during sudden load changes that result primarily because of a GTG trip or the trip of a large power consumer such as an electric motor.

The specific objectives were as follows:

- Determine the feasibility of managing an island power grid in the 300-400 MW range with a Frame 9E based power generation system
- Minimum necessary number of Frame 9E Gas Turbines to be installed
- GT capability when operating in Island mode facing sudden load changes
- Best power management configuration
- Amount of load shedding needed to keep the system alive in case of excess of loading.

It was determined that a Frame 9E based power generation system is feasible and can maintain stable operation of an island power grid if care is taken in designing the power management system (PMS). As the design matures a more detailed electrical dynamic simulation should be conducted to optimize the PMS.

A system of 5 units in an "n+1" configuration (idle spare) is feasible based on the results of this study. Static simulation results suggest that at least two units should operate in isochronous mode to improve the system stability; if an isochronous machine trips is possible to automatically switch another unit to isochronous. The capability of the whole interconnected system would improve in case all units are operated in isochronous mode at same power level (Isochronous Load Sharing), but since the stability of the system it's also affected by the way the loads are managed from the plant a more detailed analysis need to be performed on the detailed knowledge of the loads and their usage.

Both the static and dynamic simulation results indicate that when the unit is in lean-lean mode (for a DLN combustion system) a 25% load step per GTG is feasible without tripping on under frequency or voltage

drop, the same capability is always true for a standard combustor. Therefore a 330 MW system operating with an idle spare (4 @ 82.5 MW) will remain stable in the event of a GTG trip (3 @ 110 MW). If the total power requirement exceeds 330 MW a load shedding system will be implemented. The tuning of the PMS parameters should be optimized to reduce the load shedding requirement. The system was found to be especially sensitive to the under frequency trip threshold.

4 Summary/Conclusions/Perspectives

Modular replacement system

□ Systems similar to the one we designed for the modular replacement are used in industrial testing facilities with a similar weight range, however these equipments have never been used on turbine so far and testing is recommended before field application.

Barge deck stiffness

□ Depending on barge deck stiffness there will be a sink of the supporting elements (gimbals, bulks, cart rails, etc.) while the module is shifted. This effect must be considered in order to minimize stress concentration at the rail connections coming from uneven sinking of supporting elements. A first guess value is $1e9$ N/m stiffness.

We estimated that by setting such a deck vertical stiffness the maximum sink would be roughly 2 mm.

Gimbals Design

□ Gimbals as currently preliminarily selected will be able to guarantee the train to operate safely under the most extreme loading conditions as long as an appropriate detail design will be made to minimize stress concentrations. During analysis a range of motions were considered including a 50 to 70% increase from the generic motion case. However looking the results we are still way below the limits both for gimbals plate stress and bolts load (normal and shear). On a floating environment those spherical supports will be subject to cyclic loading and fatigue analysis must be carried during detail design to wave any crack initiation occurrence within the lifecycle time. British standard "Fatigue design and assessment of steel structures" practice will be followed to determine a correct elements thickness and shape to withstand the the extreme conditions.

Baseplate Design

□ During analysis a range of barge motions were considered and the accelerations and motions were increased by 50 - 70% of the generic case. Since analyses of the three-point baseplate are all in linear elastic domain, solution can be linearly shifted. However looking the results we are still below the limits in terms stress even after increasing them by 70%. For what concerns baseplate deformation and gimbals settlement assuming twice the accelerations the displacements will still remain limited in terms of baseplate global motion probably requiring some local reinforcements during detail design in case the 8 mm maximum bending would not be acceptable.

□ At the end of each harmonic analysis of the baseplate cross response in vertical direction have been extracted for each reference node. For the train lateral analysis the effect of the cross terms were not included due to software limitation assuming that these contributions will not be significant for the main rotor response. During detail requisition study a more accurate investigation might be required to guarantee that the overall train response will be suitable waiving any unexpected dynamic behavior.

These activities will be directly linked to the baseplate detail design.

GT Flange to Flange analysis

□ Adapter could be redesigned to have a larger diameter (same as load coupling) to prevent material yielding during a Synchronization Out of Phase.

□ The Unbalance Response has shown vibration levels acceptable and there is not a huge variation between foundation stiffness and baseplate configuration. There are no recommendations regarding the application on floating environment.

□ Since there is not a significantly change between the baseline and the barge mount, there are not specific recommendations coming from the casing clearance analysis.

□ During operation should be respected the tolerance on the out-of-plan between the four mounting points of the gas turbine, in order to minimize twisting and distortion on the casing. This translates in an appropriate baseplate stiffness to withstand the operating loading conditions

□ When the unit is not operating (e.g. during a storm), it is recommended to lock the rotor to avoid rotor movement without proper bearings lubrication. The rotor can be locked by a flange installed on the cold flange (inlet side). The installation of the locking flange requires approximately two or three hours and two or three people.

□ To monitor the acceleration of the barge GE would suggest the installation of proper devices on the deck able to measure the acceleration of the barge in proximity of each GTG.

GT Bearings

□ Bearing pressure is the parameter that limits the maximum motion the gas turbine can withstand. Increasing the allowable pressure leads to the following consequences:

- Reduction of oil film thickness: is estimated that increasing the acceleration from 1g to 1,2g the oil film would change from 2.1 mils to 1.9 mils;
- Increasing on Bearing Metal Temperature and Oil Drainage Temperature; those temperatures are monitored and the alarm is set to protect the unit.

Therefore the high bearing pressure can be detected by high bearing metal temperature and installing specific devices to monitor acceleration on the deck should be considered.

Oil System

□ Due to barge pitch and roll oscillations oil tank must be thoroughly studied during detail design to incorporate appropriate volume partitions to mitigate the risks of oil waves.

□ The following steps could be kept into account to improve the oil drainage capability of the system:

- The limitation on heave on the slope #1 could be overcome considering a piping redesign or an “Ejector” application. The Ejector solution was never developed for Fr9E but is largely applied in offshore gas turbine and could be studied also for this specific application. The proposed possible solution to increase the drainage system capability are:

- _ Piping redesign;
- _ Ejector application;
- _ Vent pipe application;
- _ Combination of the solution proposed above;

Each solution would require further studies and deeper investigation.

- The limitation on the horizontal drain pipe on the bearing n°2 can be overcome by a piping redesign and changing the hole position on the GT baseplate. It would give a 5.28° of motion capability.

- For the South configuration would be required to re-design the oil feeding of the IGV and Gas Module.

- In order to optimize the drain boxes configuration, the final height of the drain boxes will be calculated starting from the max allowable heave or the operating condition of the GT.

Maintenance

□ On-board workshop dedicated for turbine module maintenance is recommended instead of transportation of the gas turbine and baseplate to an onshore shop for overhaul. Either option is feasible if the material handling challenges can be overcome.

Operability

□ From the analysis of operability simulations has been noticed that the engine’s behaviour, in terms of frequency recovery, is strongly affected by PMS capability and especially by the threshold frequency set for the first stage. Due to the GT high power level, during the load step transient phase the exhaust temperature control intervene (FSRT < FSRN). If the unit is controlled in Isochronous mode and the difference between the speed control demand (FRSN) and exhaust temperature control demand (FSRT) exceeds 6% (FRSN – FSRT > 6%), the control system automatically switches from isochronous to droop to protect the engine; due to low response of the droop control, the frequency cannot be recovered to the nominal value and the GT will operate at a lower frequency depending on load and droop characteristic. In the case 3-new simulation, since the system during transient is controlled by FSRT only small difference in stage 1 threshold could cause the switching from Isochronous to droop control.