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FULL SPEED STRING TEST ON LM6000PF GAS TURBINE DRIVEN REFRIGERATION COMPRESSORS

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ABSTRACT

Chevron Australia, as part of the Wheatstone Project, constructed a two train liquefied natural gas (LNG) facility and domestic gas plant at the Ashburton North Strategic Industrial Area, 12 kilometers west of Onslow on the Pilbara coast of Western Australia. A driver selection study was performed based on the ConocoPhillips Optimized Cascade® natural gas liquefaction process. Details of this driver selection study are covered by Shah et al [1]. This driver study evaluated a variety of project-specific parameters and resulted in the selection of a General Electric LM6000 PF aeroderivative gas turbine.

The final decision to use the LM6000 engine was based on a detailed technology qualification program. Following the completion of the technology qualification, a detailed risk mitigation plan was developed. The plan was incorporated into the purchase order of the equipment and, subsequently, incorporated into the equipment manufacturer's Failure Mode Effects Analysis (FMEA) process. The risk mitigation plan highlighted extensive testing requirements during the full-load, full-speed (FLFS) string test. This paper covers the details of the FLFS testing that was performed in the fourth quarter of 2013.

INTRODUCTION

The Wheatstone Project is one of Australia's largest resource projects – providing both LNG export and greater security of supply for domestic gas production.

At the time of writing this paper, the Wheatstone Project was a joint venture between Australian subsidiaries of Chevron (64.14%), Kuwait Foreign Petroleum Exploration Company (KUFPEC, 13.4%), Woodside (13%), and Kyushu Electric Power Company (1.46%), together with PE Wheatstone Pty. Ltd. (partly owned by TEPCO, 8%).

This paper covers the qualification activities that were executed as part of the FLFS string test, the string test setup and the results of the string testing.

OVERVIEW OF THE LM6000PF AND MECHANICAL DRIVE FEATURES

The LM6000 gas turbine is a stationary gas turbine that is derived from the family of CF6 jet engines. The aircraft version of the engine is called the CF6-80C2 turbofan engine and is used to drive several types of “wide body” commercial aircraft, including the Boeing 747-400.

The LM6000 gas turbine is a dual-rotor, concentric drive-shaft, gas turbine capable of driving a load from the front and/or rear of the low-pressure (LP) rotor. Before the commencement of the Wheatstone LNG Project, LM6000s were only used in power generation application. The LM6000s are not in operation and going under commissioning at the time of writing this paper, but the facility has been designed around the LM6000s; and this is the first facility to utilize these engines. To support the use for mechanical drive, a full Technology Qualification was performed.

OVERVIEW OF THE TECHNOLOGY QUALIFICATION

Chevron’s Technology Qualification Process (TQP) is a systematic process for reducing uncertainty with new technology. The approach is to break the technology down into subsystems and/or components and determine the risk associated with each. The TQP for the Wheatstone Project was started in October 2008 and the release to use the engine was granted in December 2009.

The emphasis was placed on components or subsystem with the highest degree of uncertainty because they were either new or being operated in a new set of conditions. The associated risk for the application based on the failure of an individual component was reviewed and as a result the level of qualification activity required was determined. Details of the qualification steps are covered in Shah et al [1]. At completion of the qualification process, the resulting technology development stages (TDS) for each subsystem is shown in Figure 1.

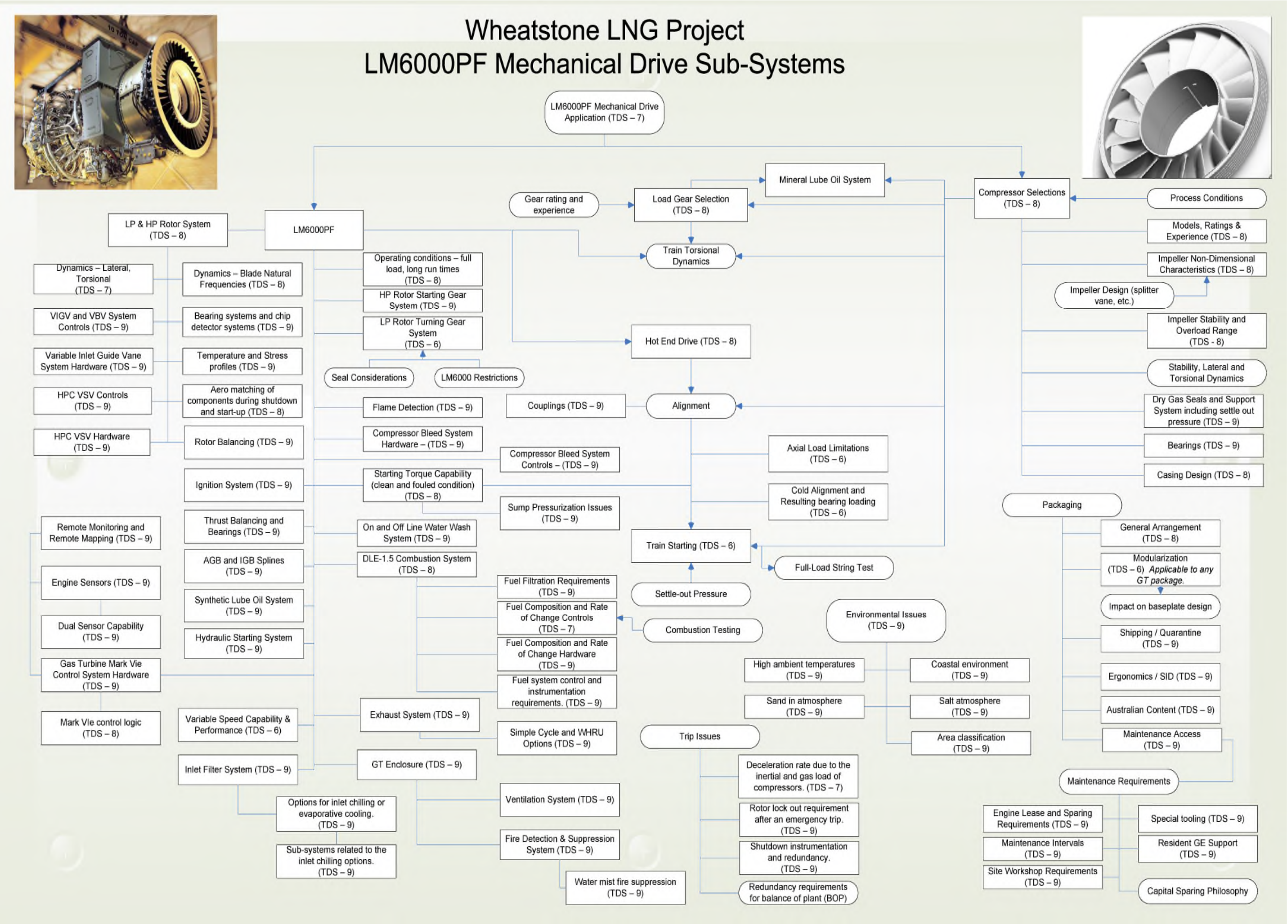

Figure 1 - LM6000PF Mechanical Drive Sub-Systems

The major risks identified for the mechanical drive application were related to the large range in fuel compositions and the impacts from not having a free running power turbine. Since the LM6000 has the gas turbine low-pressure compressor (LPC) running at reduced speeds during the compressor start, items like break-away torque and bearing sump pressure were key considerations.

Risk Mitigation Plan

Based on the items identified from the qualification phase, a risk mitigation plan was developed that became part of the equipment purchase order and integrated into the FMEA for the project. For each identified risk mitigation determined, these mitigations included a range of activities from design reviews, analysis, and component testing to full string testing. After reviewing the risks identified and the associated testing, it was concluded that the risks could be mitigated by testing only the methane compressor string and FSFL testing of the ethylene and propane strings was not required. The ethylene and propane compressors performance was validated during the component testing, and a string test was not required to mitigate the identified risks.

A FLFS test for the methane string was required to validate the performance of the LM6000PF in a mechanical drive application. In addition to the general requirements stated in API 617 for a FLFS string test, the following items were included in the scope of the string test to mitigate risks for the LM6000PF application:

- Train starting from settle-out conditions
- Train torsional dynamics
- Compressor stability for the HP Methane Compressor

- LM6000PF thrust loading
- Operation of the inlet and evaporative cooling system
- Operation of the turning gear and water washing system
- Capability of the Mark VIe/S and B/N System 1 controls
- Thermal and aero performance under full-load conditions
- Gas turbine stability through rapid changes in fuel gas composition
- Validation of the mechanical drive variable geometry schedules in string test setup
- Validation of the gearbox vibrations in light of the pinion shaft modification

The following sections describe the testing scope and setup to validate the above items.

String Test Scope and Setup

The string test allows for the confirmation of system related issues, such as string torsional and lateral dynamics, as well as starting torque characteristics that cannot be validated by individual component testing. This helps to ensure that the equipment will work properly in the plant.

The string test gas loop is composed of 3 independent gas loops.

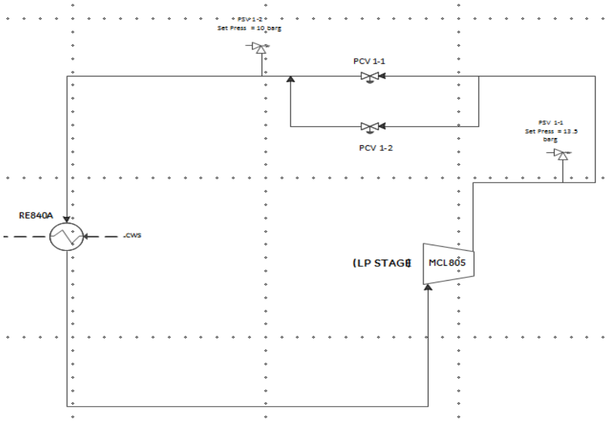

Figure 2 - String Test Setup Low Pressure (LP) Methane Compressor

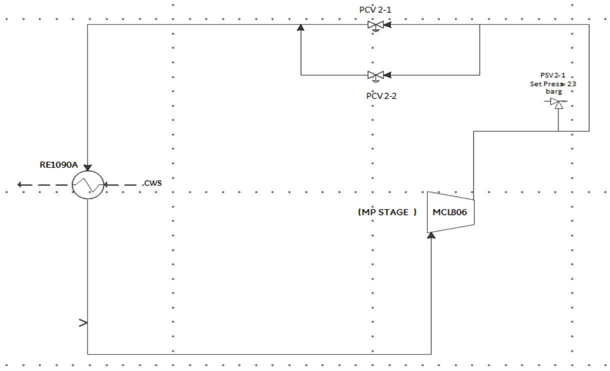

Figure 3 - String Test Setup Medium Pressure (MP) Methane Compressor

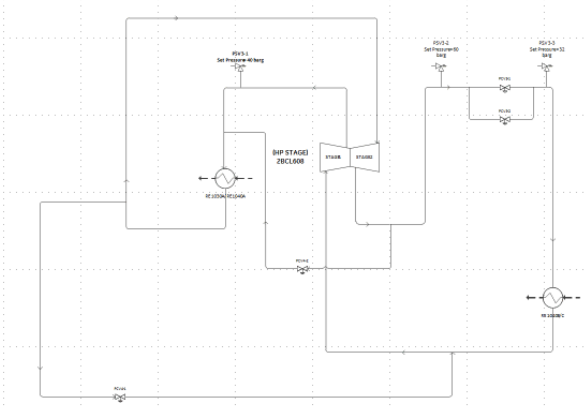

Figure 4 - String Test Setup High Pressure (HP) Methane Compressor

The tested shaft line is composed, left to right, by the LM6000PF (hot end drive configuration), MCL805 (LP compressor), MCL806 (MP compressor) and the 2BCL608 (HP compressor). Figure 5 gives an idea of the string test shaft line. The process of interconnecting piping was designed and erected in Massa for the string test, with the filter house, the VBV duct and the related supporting structure.

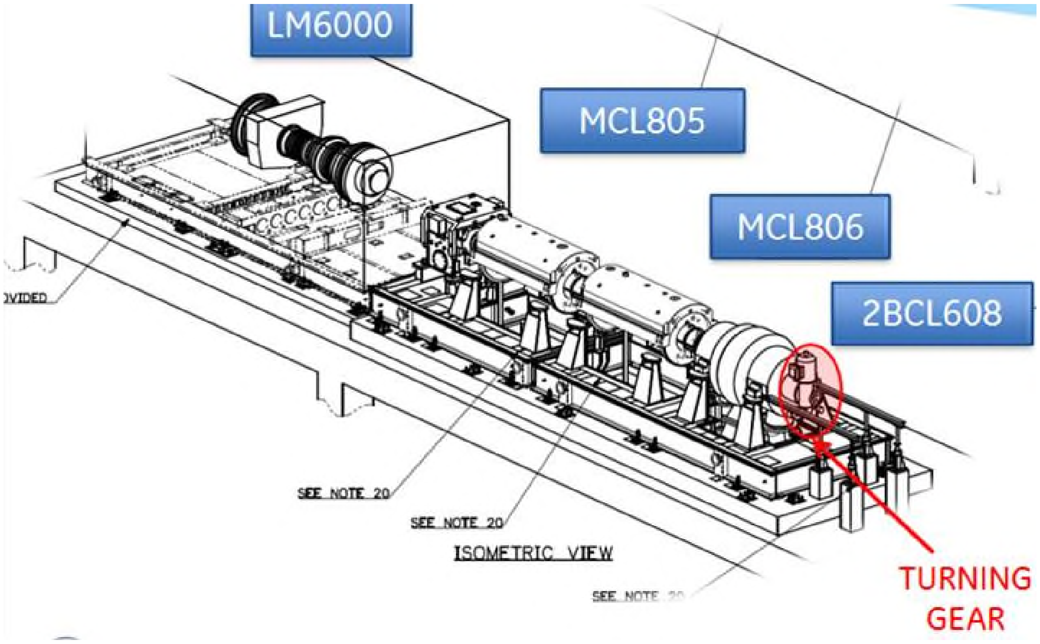

Figure 5 String Test Shaft Line

Figure 6 String Test Setup

During string testing, monitoring of all machine parameters was done to verify the machine's critical mechanical parameters: rotor and casing vibrations, lube oil pressures, temperatures, flows, seal gas system etc. The gas loops in the string test setup are designed to run the equipment at full speed, full load and to verify the performance curve from minimum operating speed to maximum continuous speed. For Wheatstone, the loop piping diameters and valves were increased in size to reduce line losses and to allow extended testing past the end of the published compressor curve to understand the compressor behavior in deep choke.

The ambient temperature range in Onslow is from 7 to 52°C. The ambient temperature range impacts the refrigeration compressors operating points, since they are rejecting the heat to the atmosphere through air-cooled condensers. Separate qualifications were performed to approve the use of T5.3 impellers for the Wheatstone project to improve the operating range of the compressor and to allow full use of the power available from the gas turbine at all ambient conditions, while minimizing the need for recycle. As part of the string test, the ability to validate the complete operating range including deep choke was performed which provided further validation to the impeller selections and performance in addition to CFD, model testing and individual machine testing.

As part of the full-load string test, a deep choke exploration of the centrifugal compressors is also performed in order to assess the “real” right section of each compressor curve. This additional verification was an interesting challenge for the gas loop design. The figure 7 shows the test results from the deep choke exploration of each compressor section (the red dot is the operating point).

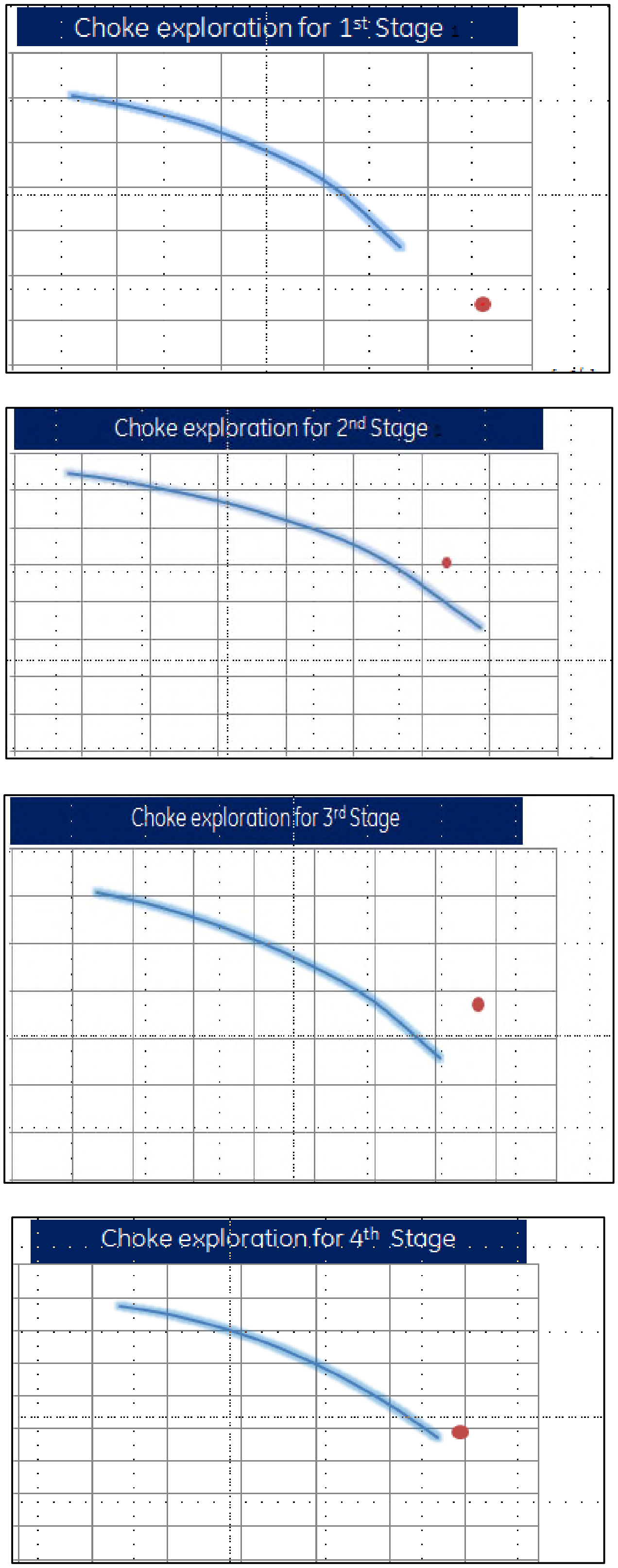

Figure 7 – Deep Choke Exploration

(Note: X and Y axis scale intentionally removed due to data confidentiality reasons)

BACKGROUND AND STRING TEST UNIQUE FEATURES AND RESULTS

Background: Fuel Flexibility Testing at Engine Manufacturer's Jacinto Port Facility

The string test was done on a LM6000 PD, which is one of the predecessor engine models to the engine (LM6000 PF) used for the Wheatstone LNG project. The scope of the test was to validate a new software logic aimed to improve the engine's response to very rapid (and substantial) variation in fuel gas Modified Wobbe Index (MWI). This logic, not available for the MKVIe at that time, was part of Engine Manufacturer's (Aviation Division) New Product Introduction (NPI) program under test at that time (Oct 2012). Customer representatives were invited to observe this test to check the capabilities of the engine towards fuel MWI variations and to check how the fuel-flex skid was arranged. This logic was not implemented for the Wheatstone engines although special algorithms, such as dynamic compensation and feed-forward logic developed within Engine Manufacturer's (Oil & Gas) Florence facility, were implemented within MKVIe control system for Wheatstone project. The testing in Jacinto Port provided a good data point for fuel flexibility test setup in Massa string test facility.

The test in J-Port consisted in a (1) check of the fuel flexibility skid and hardware, (2) complete mapping of the engine with "standard" methane fuel gas, (3) step to a Low MWI fuel gas followed by a new (4) complete mapping in these conditions. Later, the Wobbe Index variations started with a goal of 10 units/minute as a minimum seeking for a stable engine operation. The test was finished with a series of UP and DOWN ramps in the MWI to check the reactivity of the control system and engine responsiveness in respect to severe variations in the fuel gas composition.

The fuel flexibility testing skid available in Jacinto Port was much different compared to the skid designed from scratch for the Massa String Test. It consisted of a truck with a reciprocating high-pressure pump normally used for hydrocracking applications aimed to guarantee the nitrogen supply at the desired high pressure. With a mixing drum, a Gas Chromatograph and a Wobbe Index Meter, Engine Manufacturer was able to obtain the required MWI and then perform the fuel flexibility testing. However, due to presence of the reciprocating pump, disturbing pulsating oscillations in the fuel gas pressure were observed creating a few issues in reaching stable operations at low MWI conditions.

Combustion Systems

Operation of a gas turbine in an LNG facility typically results in challenges related to fuel flexibility. Specifically, the nitrogen that is included in the feed gas to the facility is not liquefied and accumulates in the fuel gas system of the facility. The nitrogen content of the fuel gas to the LM6000s varies between 6 mole percent to 14 mole percent depending on the operating conditions. Variations of other gas constituents are minor in comparison to the variation of the nitrogen content. Additionally, the rate of change for the fuel can reach 7% Modified Wobbe Index per minute.

LM6000PF handling both the large range of fuel gas compositions and the high rate of change were included in the high risk items during the qualification process. Fuel system testing was conducted at multiple points through the project. Testing of the fuel system was performed in Jacinto Port, Texas to understand the full capability of the engine with regards to the range of Modified Wobbe Index (fuel heating value). Testing of operational flexibility with DLE mapping parameters optimized for 25 ppm NOx was performed in Evendale, Ohio and extensive DLE mapping and rate of change testing was performed in Massa, Italy during the FSFL string testing.

DLE Mapping for String Test

Prior to the string testing, extensive mapping was performed on the LM6000PF engine. This mapping was focused on extending the operating window for each burner mode, understanding the influences of the LP rotor speed variations and impacts of various nitrogen contents within the fuel. The influence of varying emissions limits to increase burner mode operability windows was explored. This was possible because the LM6000PF is capable of 15 ppm NOx and allowing the limit to approach 25 ppm NOx would increase the operational range of the burner windows. The larger burner mode windows provide more overlap between burner modes and result in improved operational flexibility since the LM6000 can run in multiple burner modes and still achieve the required power.

The results from Jacinto Port, TX and Evendale, Ohio testing was used as a starting point for mapping prior to the string testing. It was found that the burner mode windows for the LM6000PF were very large with significant overlap, which will ultimately improve the ability of the engine to handle fuel upsets and accounts for changes in engine performance such as the axial compressor fouling.

The mapping was found to not be influenced by the LP speed and instead, the normal method of relying on the pressure downstream of the LP compressors section (P2) was sufficient. Mapping was successfully performed with pipeline gas. Subsequently, the mapping was validated by mixing nitrogen in the fuel to closely match the MWI (Modified Wobbe Index) range for the Wheatstone Project. The Wheatstone project included logic to account for variations in the fuel split at individual burner modes based on MWI. A sample of this influence is shown in Figure 8 where it appears clear how the burning windows shows up, as consequence of the mapping and fuel flexibility active compensation.

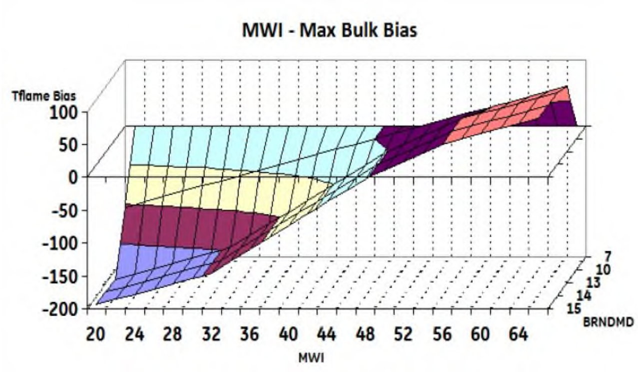

Figure 8 Mapping result with Active Compensation

Based on logic to account for the changing MWI, it was found that the mapping performed on the pipeline gas were sufficient when operating on other fuel compositions. Mapping was completed for all burner modes and the FSFL string test was able to proceed.

Fuel Rate of Change and Fuel Flexibility Test Setup at Massa String Test Facility

One of the higher risks for the application in an LNG facility is the ability of the LM6000PF engines to handle rapid changes in fuel gas compositions. The facility has the ability to handle the rate of increase in nitrogen as it is brought online, and the nitrogen accumulates in the fuel system. However, in the event of a trip of an LNG train, the volume of the fuel header system is one of the few parameters that can be varied during design to slow the fuel composition (MWI) rate of change to the gas turbine, as the source of nitrogen is lost from the fuel and the fuel source switches to coming directly from the feed gas. Extensive simulation was done during the FEED and early EPC phases of the project to understand the potential rate of change of the fuel MWI. Based on these simulations, a worst case rate of change of 7% MWI/min was determined in the event there was an LNG train trip. To provide additional margin and account for uncertainties associated with the modeling, a target value of 10% MWI/min was applied. This target was applied in both increasing and decreasing MWI while in actual practice the high rate of changes would only result in increasing MWI. The decreasing MWI is the most severe case since it can result in a loss of flame within the combustor and trip the gas turbine.

From a gas turbine standpoint, one gas can be considered to be interchangeable with another gas if, when they are used, there are not significant variations in the performance of the gas turbine (GT) engine. The most important parameter usually evaluated for verifying the interchangeability of different natural gases is the Modified Wobbe Index (MWI). The MWI is an index indicating the size of heat input energy with respect to a combustor according to a fuel component and may be expressed as a function of a heating value and specific gravity. If two fuel gases have identical Modified Wobbe Indexes, given the same pressure, valve settings and other conditions, the energy output will be also identical.

The test had the objective to demonstrate the gas turbine stability through rapid changes in gas composition (up to10% Wobbe Index (WI) per minute rate of change). In order to perform the test, a variable amount of nitrogen was added to the fuel gas to control the WI.

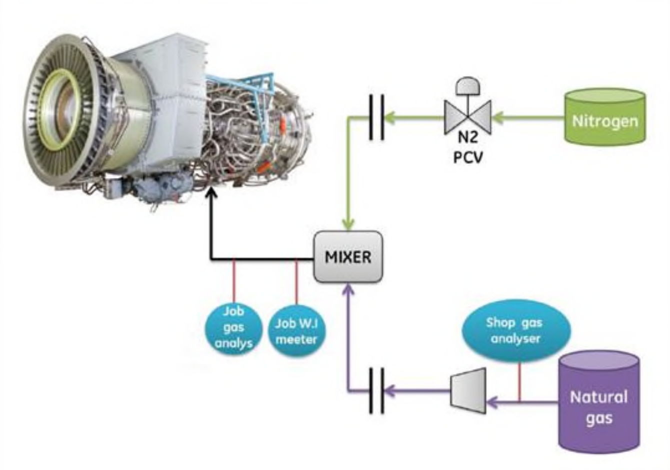

Figure 9 Fuel Flexibility Test Setup

Learning from the experience of fuel flexibility testing at Jacinto Port, the fuel flexibility skid in Massa were designed by selecting a cryogenic, centrifugal variable speed pump, evaporators, pressure control valve, nitrogen flow meter and a counter-flow mixing drum to improve the mixing. Starting from the design Wobbe Index, the Nitrogen control valve was controlled in order to achieve the target MWI in a given amount of time. The Nitrogen flow needed for control was estimated by the MWI measurements and calculations done in MKVIe. The results of the string test showed a very stable operation even in very low MWI conditions, proving the better design of the skid in terms of control and stability of the fuel gas stream.

The rate of change in both directions was tested during the FSFL string test for 1%, 5%, 10% and 20% MWI/min rates. The gas turbine combustion system was monitored for impact on acoustics, stage down events and variation in LP rotor speed. Fuel rates of change of up to 20% MWI/min were successfully demonstrated without stage down events or high acoustics and the speed variation was small and considered acceptable. The following figure 10 is an example of the 10% MWI/min trend that was part of the FSFL testing campaign.

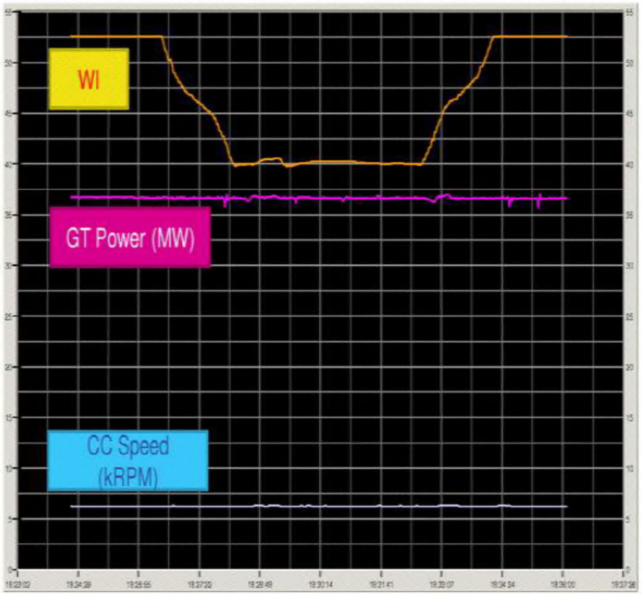

Figure 10 - Fuel Flex Results - 10% MWI/min Rate of Change

The following data and figures show the overall test results, especially the engine response, due to fuel rate of change.
Engine response at 10%/min (refer to Figure 11):

- Negligible power and speed oscillations (engine running at 3,780 rpm, ~37 MW (Note: In the figure, the scale is difficult to see and the variations seem larger than we actually experienced.)
- NOx and CO always below contractual limit
- No acoustics

Figure 11 - Engine response @ 10%/min

Engine response at 20%/min (refer to Figure 12):

- Limited power and speed oscillations (speed within 2%, power within 7%)
- NOx always below contractual limits (CO temporarily exceeding limits
- No acoustics

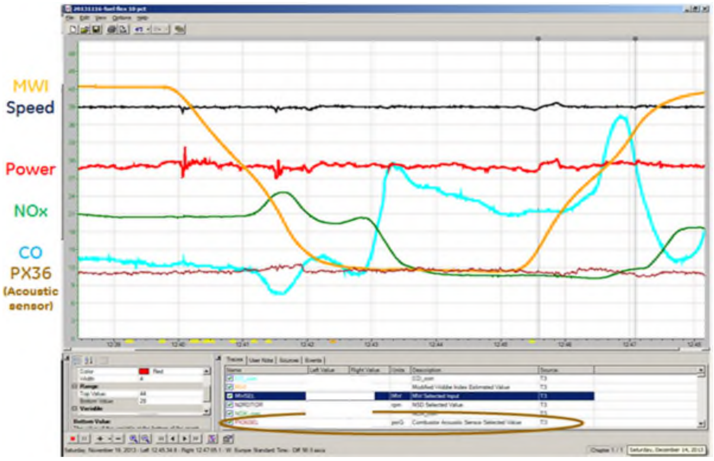

Figure 12 - Engine response @ 20%/min

The rate of change testing successfully demonstrated the capability of the LM6000PF to exceed the fuel flexibility requirements for the Wheatstone Project.

Starting Considerations

Establishing the Starting Torque Capability

Prior to finishing the technical qualification, an LM6000PD was installed in the Jacinto Port, Texas test facility and the LP rotor was locked into position with load cells. This was done to measure the break-away torque that could be developed by the LM6000 engine to establish the capability to start the compressor string without the aid of starting motors, jacking oil systems or turning gear systems.

During this test, the engine exceeded 16,500 N-m of torque before test stand limitations related to the exhaust temperature were reached. For the Wheatstone Project the measured break-away torque exceeded the project requirements so the actual engine capability was not determined. At 16,500 N-m, no engine limits were reached and instead only the limit of the allowable stack temperature was reached.

As described separately, the LM6000PF strings for the Wheatstone Project are equipped with both jacking oil and turning gears to support the offline water wash requirements. To support the offline water wash, a two-speed, turning gear system was included with a high speed of 260 rpm. These systems were demonstrated during the string test, but not used to assist with the break-away for the string during any of the gas turbine starts.

Variable Geometry Schedules

For power generation applications, the LP rotor accelerates to 3,600 rpm at very low load prior to synchronizing to the electrical grid. For mechanical drive applications, there is a load on the LP rotor from the very beginning because of the gas compression taking place in the driven centrifugal compressors. For the power generation application, the LP compressor Inlet Guide Vanes (IGV) are at their minimum setting and the Variable Bleed Valve (VBV) between the LP and HP compressors is open to bleed off excess air as the unit is starting and during operation at low load with the LP rotor spinning at 3,600 rpm. This is done to minimize the load from the LPC and to match the air flow between the LPC and HPC.

For the mechanical drive application, the HP rotor is spinning up to provide thrust during the starting phase and is “pulling” air through the LPC. Under this condition the IGV needs to be *opened* to minimize the restrictions; and the VBV needs to be *closed* to prevent pulling dirty air in from the atmosphere. A considerable amount of effort was performed during the qualification phase to ensure that the schedules developed for the IGV and VBVs allowed the mechanical drive unit to operate under all the various load and ambient temperature conditions associated with a compressor drive application.

Validation of the mechanical drive variable geometry schedules was first performed in Evendale, Ohio and then utilized at the Massa String Test for the Wheatstone Project.

Settle Out Pressure Simulation in the String Test

As described earlier, the LM6000 engine has the low-pressure compressor connected to the low-pressure turbine. The low-pressure turbine is effectively the power turbine for a compressor drive application. The influence of having the low-pressure compressor connected to the power turbine was an item of risk for the ability to start the compressor strings under the full settle-out conditions. The need to depressurize compressors in refrigeration services is a loss of refrigerant, detrimental to the environment and, in the case of the Wheatstone Project, is to be minimized.

Among the string test objectives, LM6000PF pressurized start-up was one the most demanding. It is common in the LNG world to avoid depressurization of the refrigeration circuit to save refrigerates and to have a quicker start-up. Having the gas loop fully pressurized creates a demanding starting condition for the engine with a torque absorption peak at low speed.

During the qualification phase, the methane compressor string was identified, as the string requiring the highest starting torque requirement. This was the result of an initial analysis that considers the methane string having a gear and three compressor casings. During detailed engineering, the size of the process piping and the associated settle-out pressures resulted in the ethylene string requiring the highest starting torque. To ensure that the various tests performed throughout the execution phase of the project would mitigate the risks, even for the ethylene string, a late change was made to the methane string test pressures to closely simulate the expected starting torque on the LM6000PF engine in the worst case. This was done by increasing the starting pressures on the three compressor casings to the maximum pressures allowed by the test loop relief valve settings. The increase in starting pressures for the FSFL string test significantly exceeded the starting torque requirements of the methane and propane strings and was able to demonstrate the capability to start the ethylene string.

LM6000PF Start-up Results

The testing demonstrated good pressurized start-up capability of the LM6000PF, ramping up in 15 minutes from crank to full speed, with an average 41MW shaft power. The acceleration from core idle to minimum operating speed (MOS) occurred in less than 2 minutes, with an LP power output increase from 1 MW to 32 MW. Refer to Figure 13 for the start-up curve (next page).

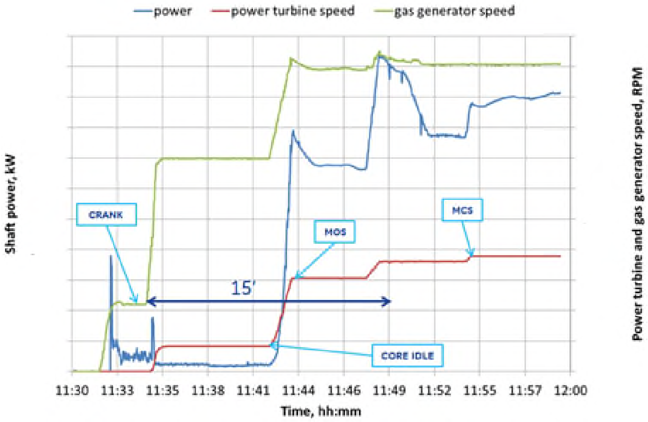

Figure 13 - LM6000PF Start-up Curves during the FLFS String Test

Lateral and Torsional Measurements

String Torsional Response

The methane string was the most complicated string from a lateral/torsional perspective with a gear and three compressor casings. The string test in Massa represented a great opportunity to gather a complete set of data concerning the possible lateral/torsional interactions between the compressors, couplings, load gearbox and the engine. The torsional measurements were performed with two independent systems: the job torque meter and a shop monitoring equipment installed on coupling between the gearbox and LP compressor. The measurement chain is schematically shown in Figure 14.

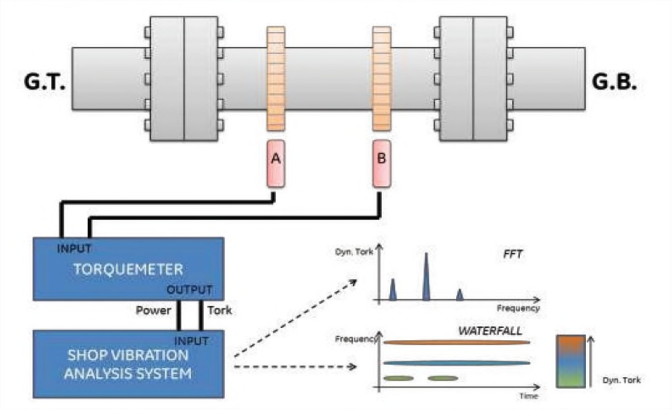

Figure 14 – Torsional Measurements Schematic

The shop equipment with B/N probes was used to monitor torsional behavior at a different measurement point and validate the results collected from the job torque meter. Table 1 below shows the torsional measurements confirming a good correlation with the calculated and measured TNFs:

Table 1 - Calculated and Measured Torsional Natural Frequencies

	1TNF	2TNF	3TNF	4TNF	5TNF
Calculated (Hz)	11.4	20.6	32.5	37.3	43.75
Measured (Hz)	11.2	22.5	32.5	X	42

During the analytical phase, it was discovered that the possibility existed to excite a fourth lateral frequency of the gearbox with a lateral/torsional interaction. This super-synchronous vibration occurring at GB HSS, due to the pinion fourth lateral mode excitation by gear speed harmonics. This response was foreseen through calculations. This phenomenon mainly involved the pinion shaft NDE side (relevant lateral mode shape) and did not show up during the unloaded gearbox mechanical running test at the gear vendor shop.

The analysis was performed using the stability analysis (Logarithmic Decrement [log dec] approach) showing coherent results, highlighting a real potential vibration risk at high frequency during the full-load string test:

- Fourth Mode Frequency = 951 Hz
- Log dec = 0.311

The proposed solution was to remove mass from NDE pinion to shift the fourth mode to 2 kHz (and a log dec equal to 0.595) as indicated in Figure 15. This modification was implemented during the manufacturing of the pinion shaft. During the string test, validation of this solution concluded that:

- The gearbox rotor-dynamic behavior was coherent with theoretical analysis.
- Gear vibration behavior was always well within the string acceptance criteria, stable with the speed and load with no abnormal high-frequency components.

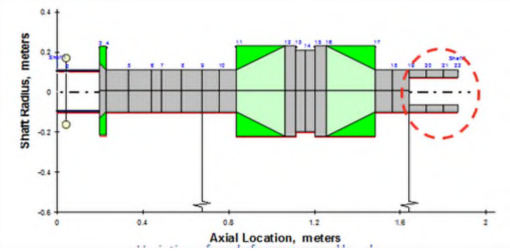

Figure 15 - Gearbox Pinion Shaft Modification

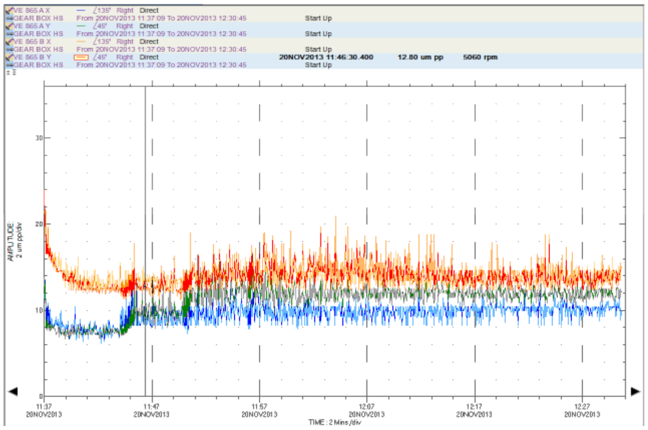

Figure 16 - Gearbox Vibrations during FLFS String Test

Axial Thrust Measurement on LM 6000 DE flange

Many of the LM6000s in power generation have been in cold-drive applications. The LM6000 retrofits for LM5000 engines have been installed as hot-end drive gas turbines. For the mechanical drive application, it was decided to utilize the engine as a hot-end drive. A large motivation for this decision was to move the gas turbine inlet system away from the process gas compressors to ensure that duct leaks could not ingest hydrocarbons if there was a compressor seal failure or other hydrocarbon leak point around the centrifugal compressors. All the gas turbine installations known to the authors are of hot-end drive configurations.

Hot end drive requires the coupling to take a larger deflection between cold start conditions and normal operating conditions. The gas turbine heats up and the shaft position moves towards the compressor and up. The compressor is in a refrigeration service with the suction at the driven end and results in the shaft contracting away from the gas turbine and down increasing the total alignment variation that the coupling needs to withstand. The axial variation between “cold” and “hot” conditions results in axial thrust loads subjected to the gas turbine LP rotor different and higher than previously experienced on generator drive applications. As part of the technical qualification activities for the LM6000 MD it was identified the need for a special measurement of the load coupling elongation to quantify the axial thrust load from “cold” to “hot” conditions. The LM6000 thrust bearing is required to work with a much higher thrust load given by the load coupling stretch. The purpose of this measurement is to validate the load coupling stretch in order to verify that steady-state axial load was within the acceptability criteria of the gas turbine LP shaft thrust bearing (1,500 Lb.).

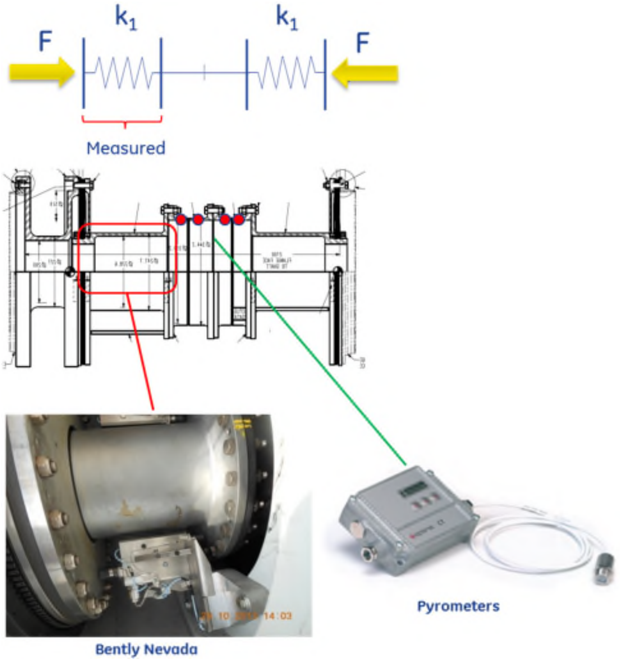

Figure 17 – Axial Thrust measurement

A dedicated modified coupling guard was used and a special cooled bracket assembly was mounted on the coupling guard to support the test displacement probes. BN displacement probes were used to measure the coupling deformation. The load coupling pre-stretch was calculated based on three different inputs: (1) the gearbox DE flange elongation, (2) the coupling elongation and (3) the engine DE flange elongation. It is to be noted that the gas turbine thermal growth accounts for 75% of the total pre-stretch (8mm). The measurements performed in Massa during the Wheatstone Methane unit string test provided a confirmation of the expected behavior of the shaft line. The measurements allowed confirmation that the maximum allowable thrust load was never exceeded throughout the test. The Ameridrive load coupling is characterized by an axial stiffness equal to 1,773 N/mm and looking at the string test measurements (Figure18), test results did show that 4.5mm out of 8mm were recovered. At maximum power conditions, approximately 6mm of the axial pre-stretch was recovered. The 3.5mm not recovered transitioning from cold to hot conditions (4 hours' full load) translated in an axial thrust on the bearing of 1,773 N/mm * 3.5 equal to 1,440 Lb.

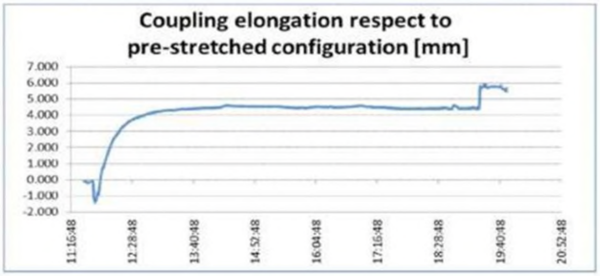

Figure 18 – Load Coupling Elongation

Facing an allowable limit of 1,500 Lb., it was demonstrated that engine thrust bearing is able to properly work within its mechanical limit even in a mechanical drive application. The difference between the calculated pre-stretch and observed growth was explained considering that the conditions of the test (i.e., limited duration of operation and essentially winter ambient temperature) were not necessarily representative of the long-term operating conditions of these units in the final site. The colder conditions at the site results in cooler enclosure ventilation air, which is also used for cooling of the load coupling and, therefore, results in less axial growth of the coupling spool. The thermal growth measured in Massa is on the lower end of the thermal growth expected during long-term operation at the site. The ambient conditions at the site are higher and the power demanded by the compressors will be closer to maximum power. This means that what was measured in Massa represents a worst case scenario in terms of pre-stretch recovery. Based on this, the decision has been made to keep the current pre-stretch values and not change the shim packs on the load coupling.

HP Methane Compressor Lateral Stability Testing

The study of centrifugal compressors self-induced instabilities is of increasing importance in the O&G world.. As a direct consequence, API 617 requires a Level 1 & 2 analysis to assess the compressors stability through the computation of the log dec of the first mode of the rotors at the operating conditions. In particular, Level 2 analysis permits to assess the destabilizing effects of the process gas flowing through the seals and bearings via dynamic force coefficients. During the initial qualification, the HP Methane compressor was identified as having the lowest log decrement of all the casings. While Level 2 stability analysis showed a log dec of greater than 0.1 as per the API 617 requirement. Despite this, the mathematical tools are now able to predict with a pretty high level of confidence the compressors stability (e.g., properly assessing the destabilizing effects); it was decided to validate the computational results during the string test with a full-load stability test (FLST). This activity was seen as a risk mitigation for all the compressor strings by validating the model. In order to perform this validation, a magnetic exciter (ME) was installed on the NDE side temporarily removing the turning gear and fixing it to the machine via tie rods on the thrust bearing casing. The ME is fed with well-defined asynchronous rotating forces with a fixed amplitude, but variable frequency acting on the rotor around the first critical speed.

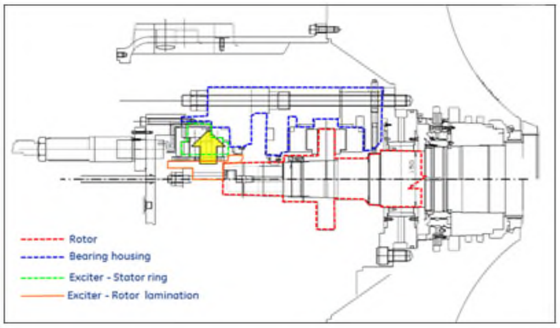

Figure 19 - High Pressure Methane Compressor Lateral Stability Testing Setup

Figure 20 - Photo of the Magnetic Exciter used during the Lateral Stability Testing of Methane High Pressure Compressor

The purpose of the test was then to check the compressor rotor dynamic stability by measuring its Logarithmic Decrement (δ) for the first forward mode of the rotor + journal bearings + seals system. Rotor is excited with ME at NDE side, and the vibration response is measured at DE and NDE side. An additional measurement plane (Kaman probes) was placed in the middle of the rotor where the mode response is higher. The test points were defined as follows in Table 2.

Table 2 – Compressor Operating points during the test

Testing Points	1	2	3
Process Gas	NATURAL GAS		
Speed [rpm]	5000	5500	6237
Inlet P [BarA]	15		
Inlet T [°C]	40		
Outlet P [BarA]	30.8	37	47.5

The rotor was excited with a continuous sine sweep and to minimize the leakage error a very slow sweep rate was selected. With a Multi Degree of Freedom algorithm (MDOF) in the frequency domain the response function was analytically analyzed. The results are shown in Table 3.

Table 3 - Experimental Log Dec of the first 'FORWARD' mode

Point	Speed	Frequency (CPM)	LogDec
1	5000	3083	0.27
2	5500	3110	0.23
3	6237	3133	0.215

The reduction of the log dec, with increasing in the compressor operating speed, is explained by the variation of the seal and bearings coefficients (stiffness and damping). At higher rotational speeds. the increased stiffness from the bearings acts to minimize the vibration amplitude that translates into a less bearings damping capability. This, in addition to increasing cross-coupling from the labyrinth seals, results in decreasing log dec values.

The ME is the typical way to assess the compressor rotor dynamic stability through a physical excitation of the rotors by mean of well-defined external forces. However, it is also possible to determine the log dec using methods that does not require any external excitation of the rotor. This class of methods is referred to as the Operational Modal Analysis (OMA) and was selected to benchmark the results obtained with the ME stability test performed. In this method, the only excitation source under analysis is the process gas flowing in the compressor. A good benchmark, with the typical stability test, would result in a great step forward in the compressors stability assessment permitting the need to avoid the mechanical modification to the compressor NDE side and the need for a ME. OMA is a recent mathematical technique that allows the stability assessment without knowing anything about the instability source (e.g., external force acting on the rotor). In this method the instability force is modeled as a Gaussian white noise that contains the exact same level of energy at all frequencies. Hence, the output spectrum is fully representative of structure information, with all modes inside the given frequency range equally excited.

The basic idea intrinsic in the OMA is that response being measured is the natural vibration of a complex system given combining the mechanical system under testing and the mechanism that generate its response. OMA was used during the full-load string test, recording the steady-state vibration signals. By using the spatial position of six vibrations probes, it was possible to build up a rotor test model. Through a complex mathematical analysis, we were able to compute the OMA results, compared to those obtained with the FLST in Table 4.

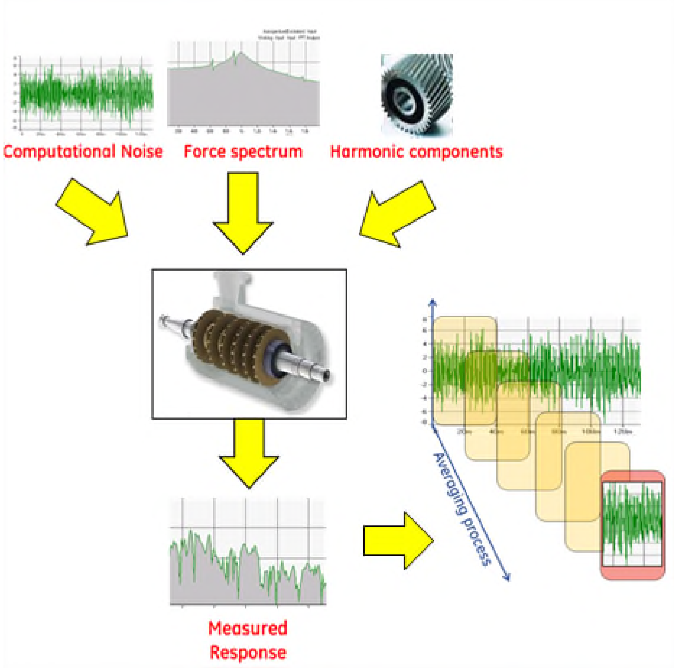

Figure 21 - Test and Measurement Setup for the High Pressure Methane Compressor

Table 4 - Measured and OMA Predicted Log Dec Values from the High Pressure Methane Compressor Stability Test

Point	Speed [rpm]	FLST		OMA	
		Freq [cpm]	LogDec	Freq [cpm]	LogDec
1	5000	3083	0.27	3060	0.27
2	5500	3110	0.23	3102	0.25
3	6237	3133	0.215	3115	0.217

As it can be seen the results are very close to each other, OMA opens up an interesting new way to assess compressors rotor-dynamic stability with no use of an external exciter. In addition, OMA can be easily applied to all those machines that are driven-through, like for example the MP and LP machines of the string that was tested.

Bode Plots for Methane Compressors, Gearbox and Gas Turbine

Starting on the next page, please seethe bode plots for the main shaft line components during start-up, shut down and 4-hour string testing. Due to size of the data, only representative Bode Plot samples from the start-up, shut down and 4-hour string test periods are shown below. The samples provide a good understanding of the overall vibration signature of the machinery components during the durations stated above. Overall, there were no vibration-related issues during the entire duration of testing and all the acceptance criteria was followed.

High Pressure Turbine

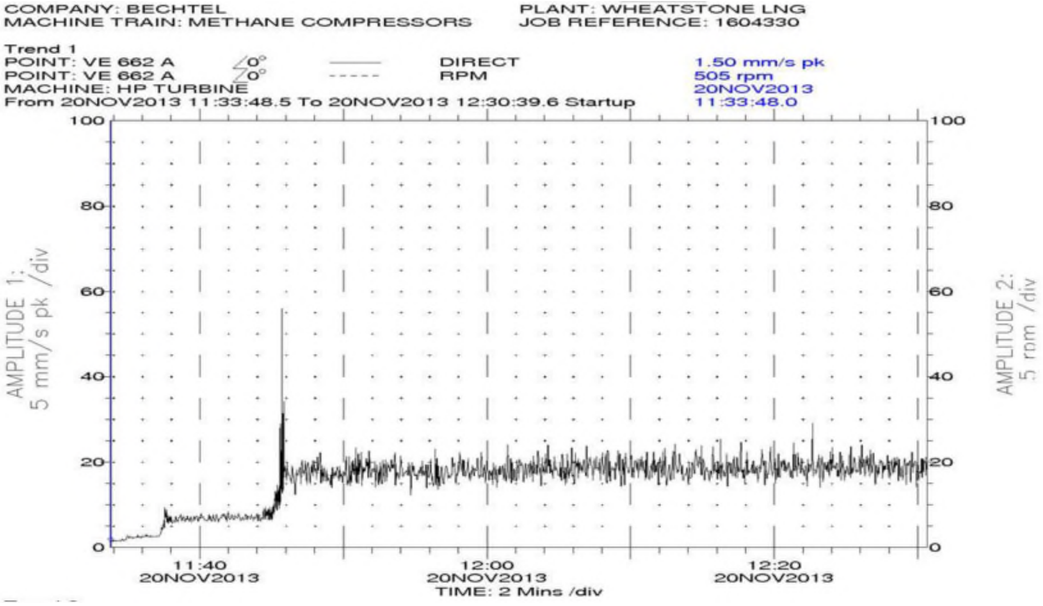

Figure 22 High Pressure Turbine: Start-up

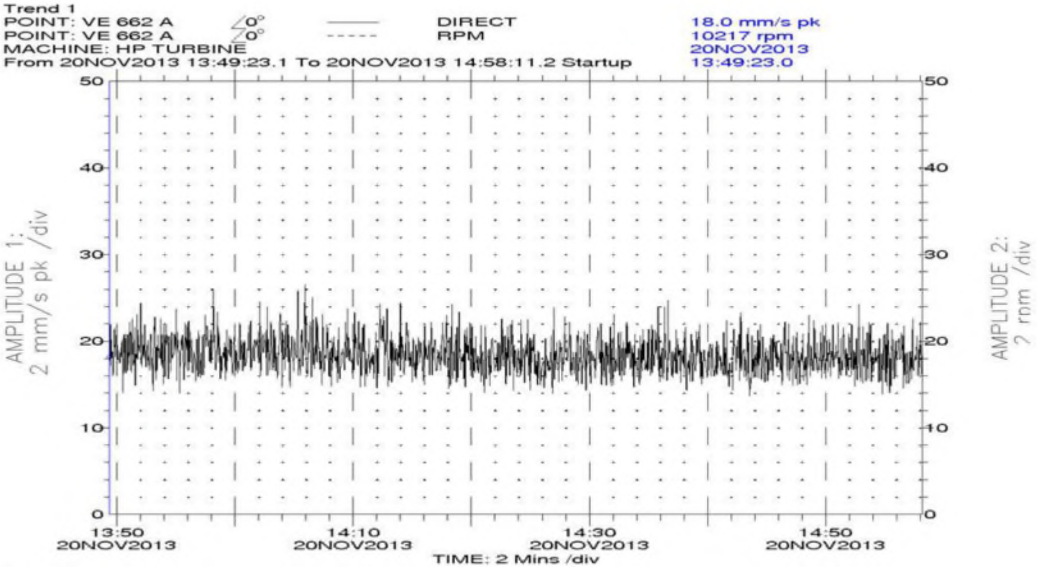

Figure 23 High Pressure Turbine: Steady State

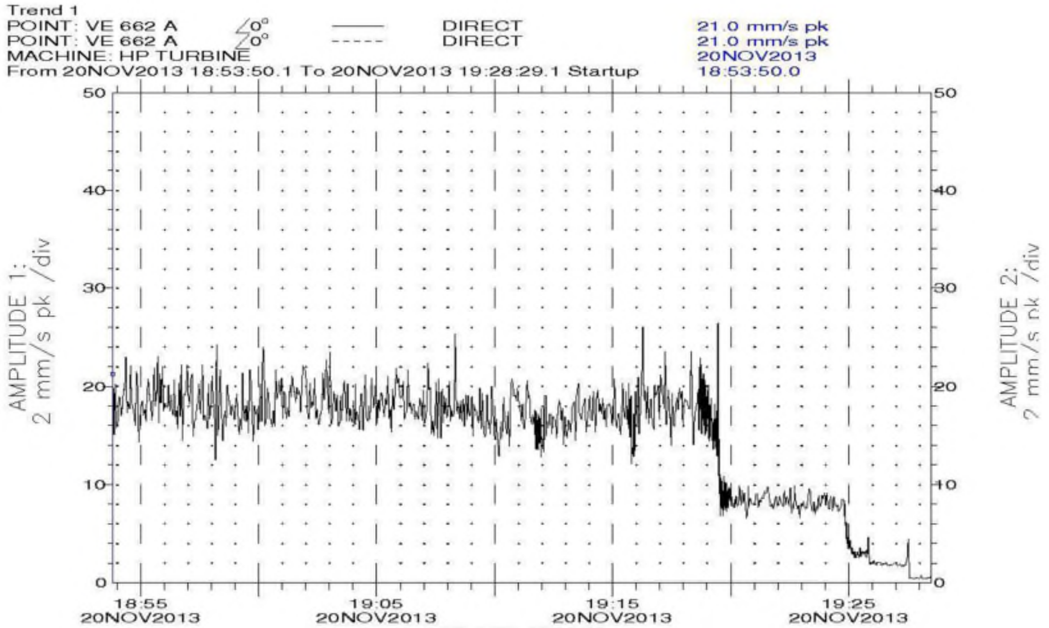

Figure 24 High Pressure Turbine: Shutdown

Low Pressure Turbine

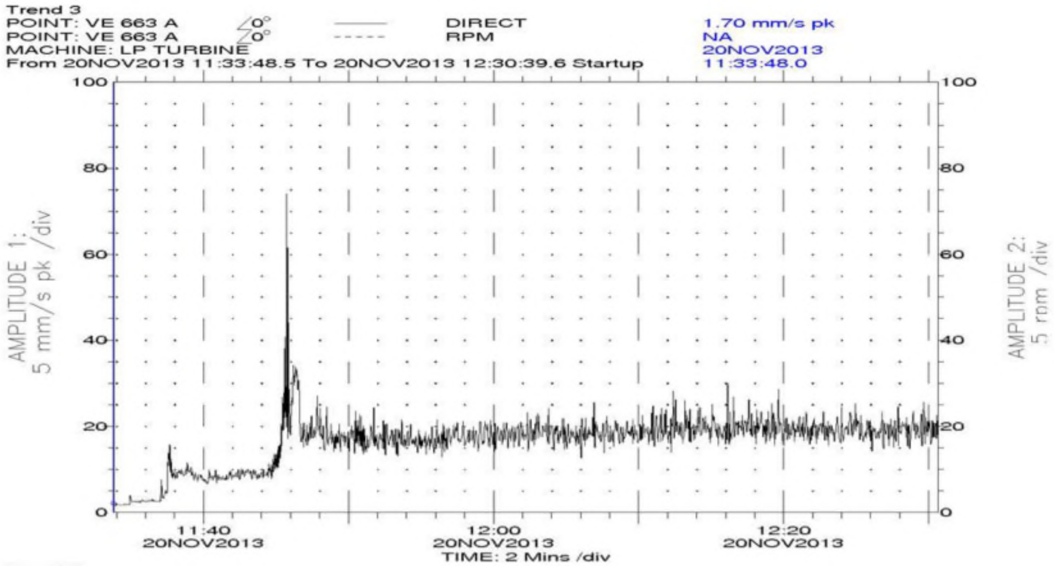

Figure 25 Low Pressure Turbine: Start-up

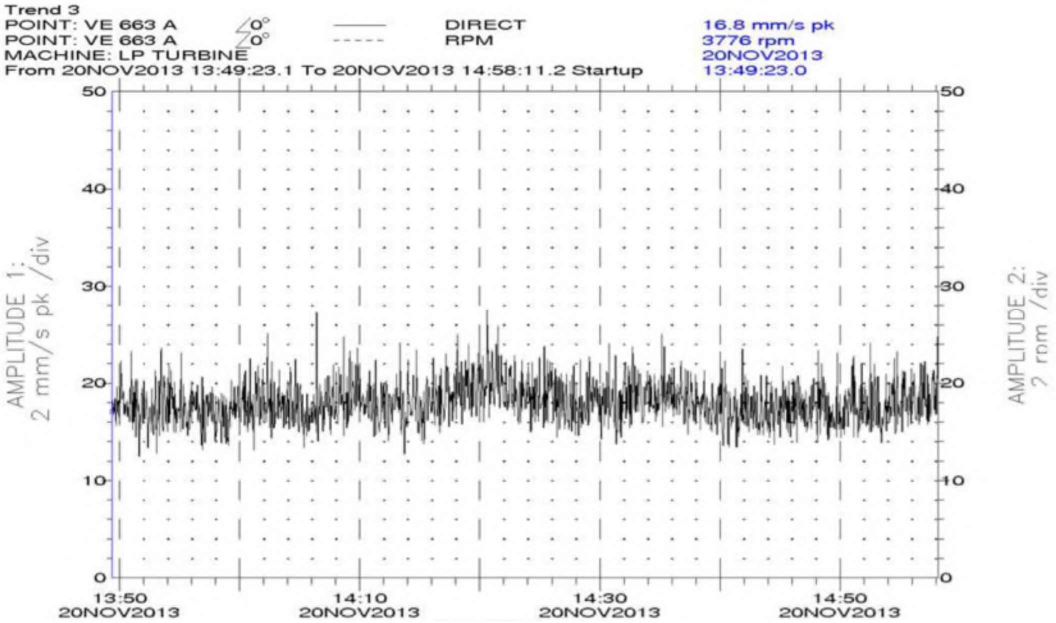

Figure 26 Low Pressure Turbine: Steady State

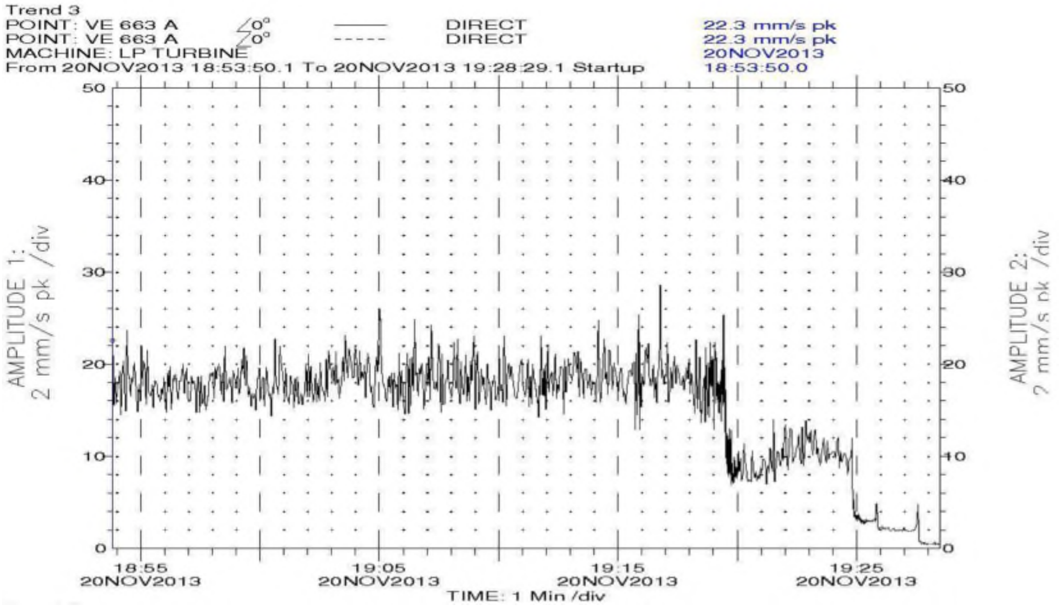

Figure 27 Low Pressure Turbine: Shutdown

Gearbox Low Speed Shaft

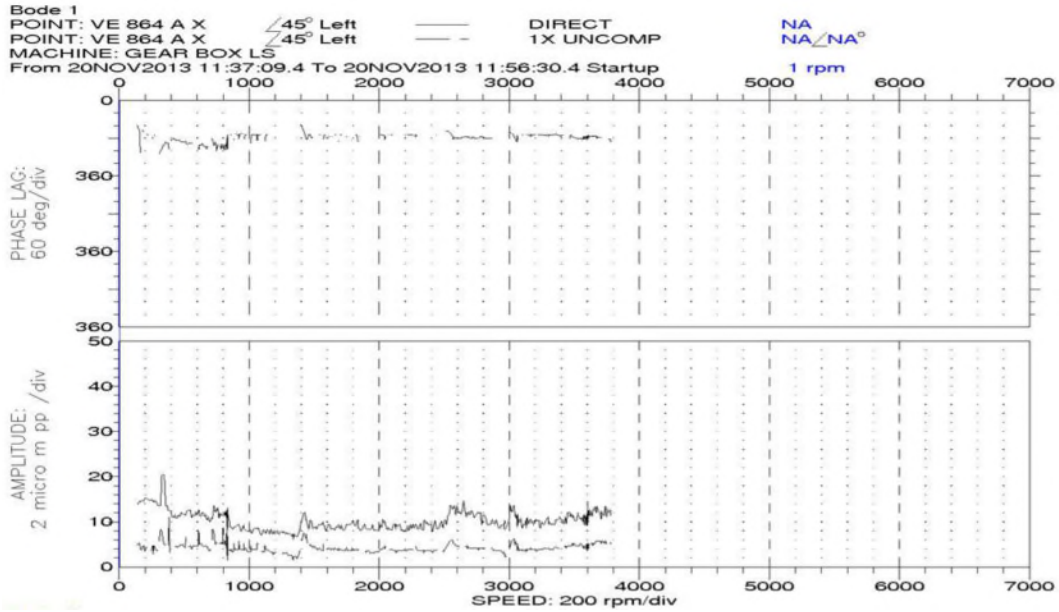

Figure 28 Gearbox Low Speed Shaft: Start-up

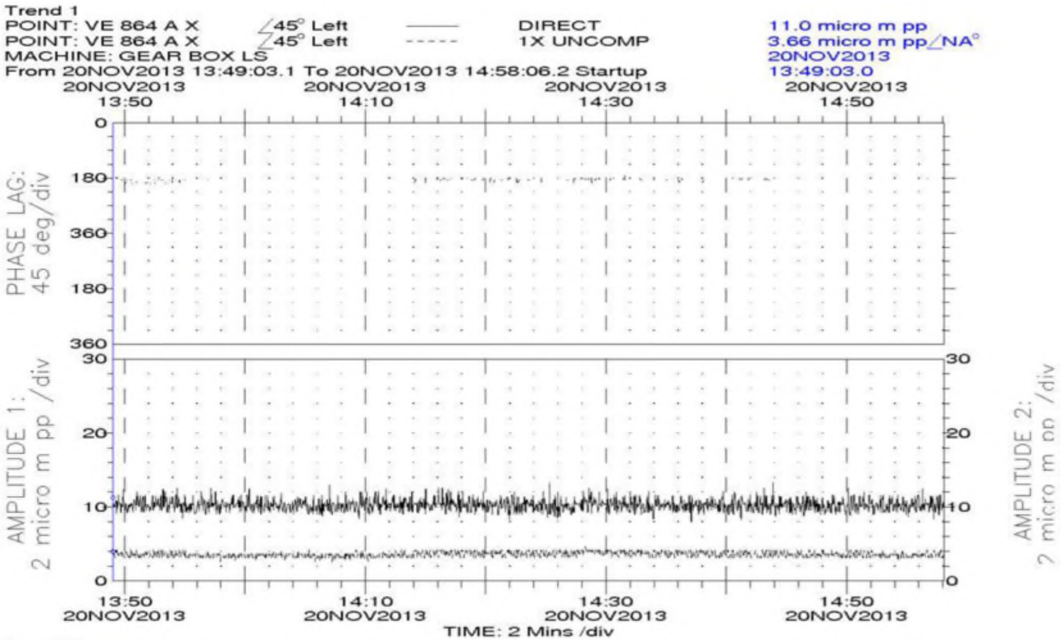

Figure 29 Gearbox Low Speed Shaft: Steady State

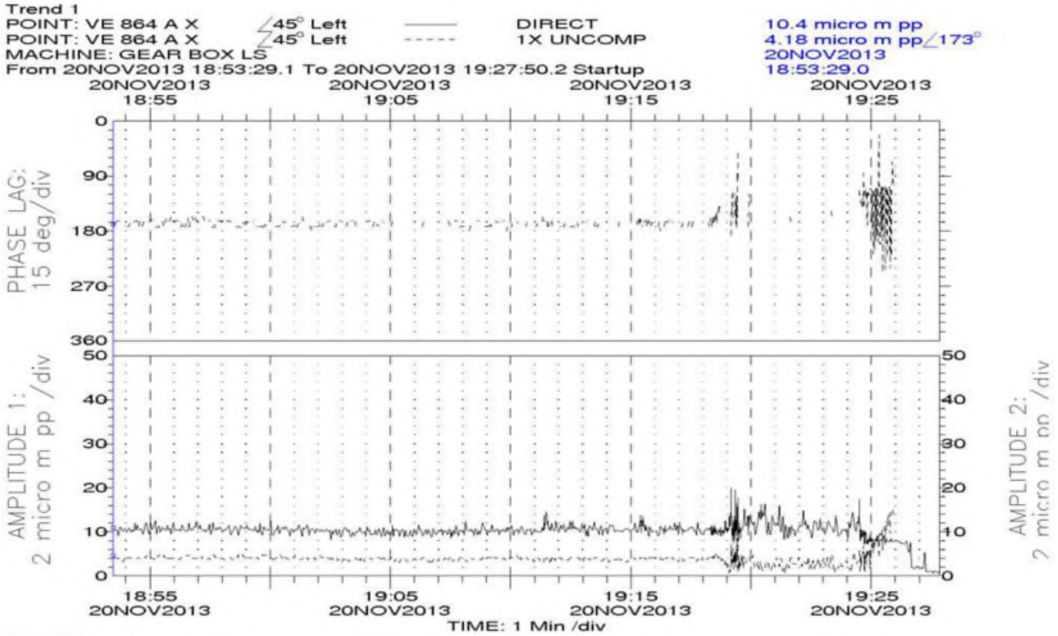

Figure 30 Gearbox Low Speed Shaft: Shutdown

Gearbox High Speed Shaft

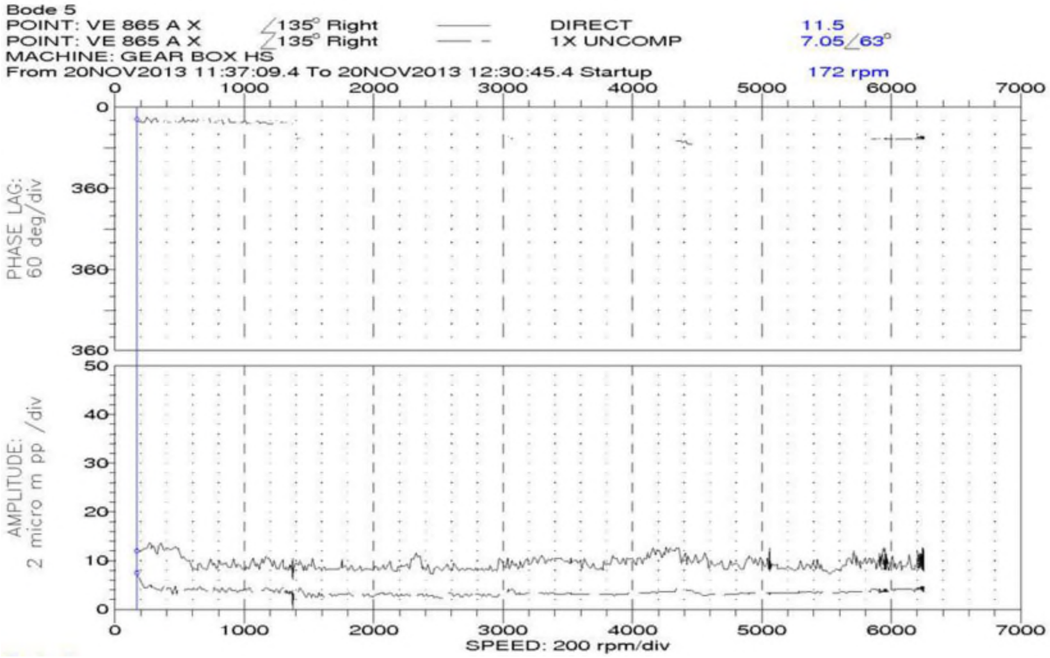

Figure 31 Gearbox High Speed Shaft: Start-up

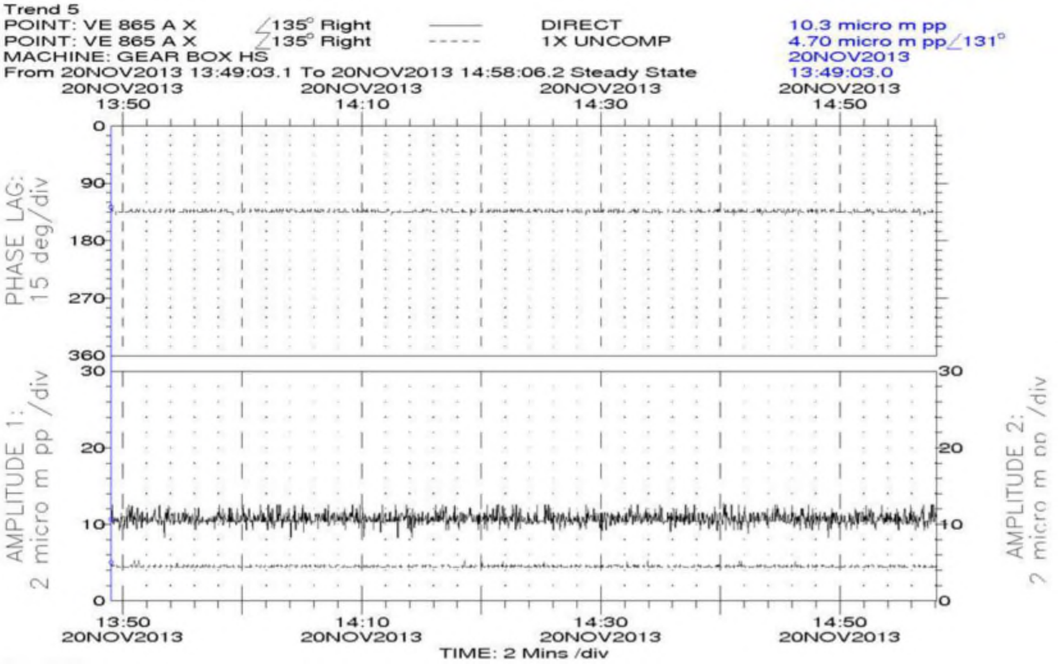

Figure 32 Gearbox High Speed Shaft: Steady State

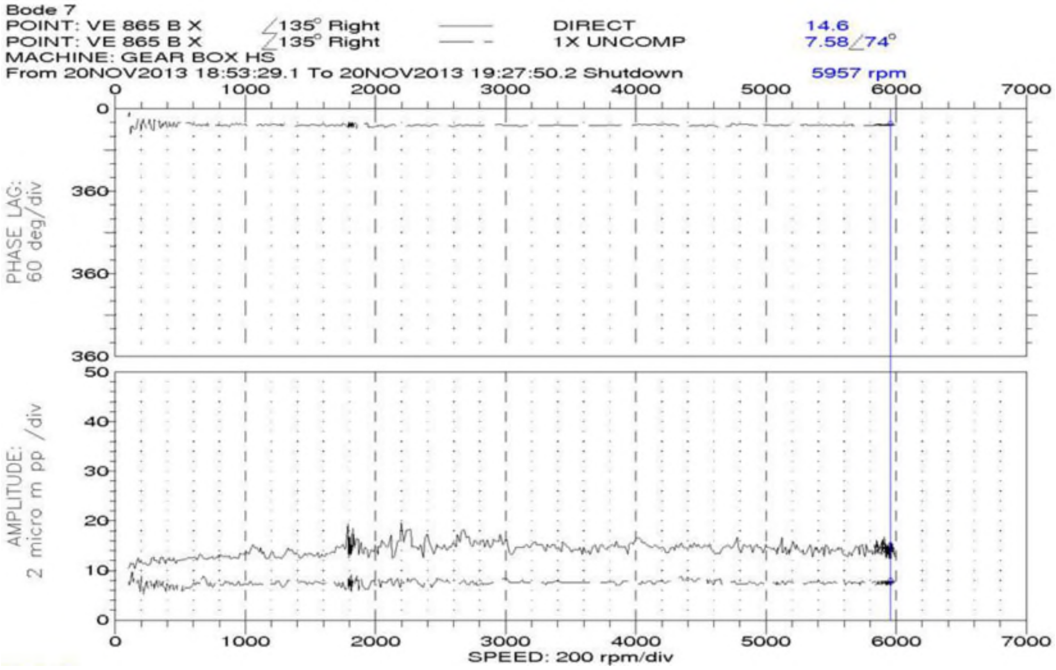

Figure 33 Gearbox High Speed Shaft: Shutdown

Low Pressure Methane Compressor (MCL 805)

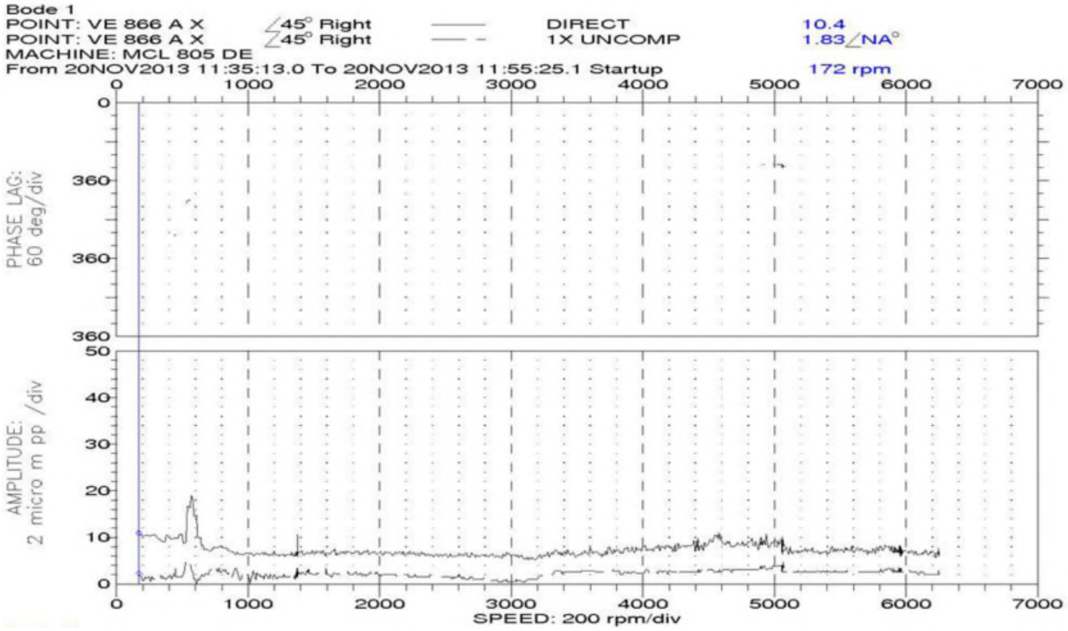

Figure 34 Low Pressure Methane Compressor: Start-up

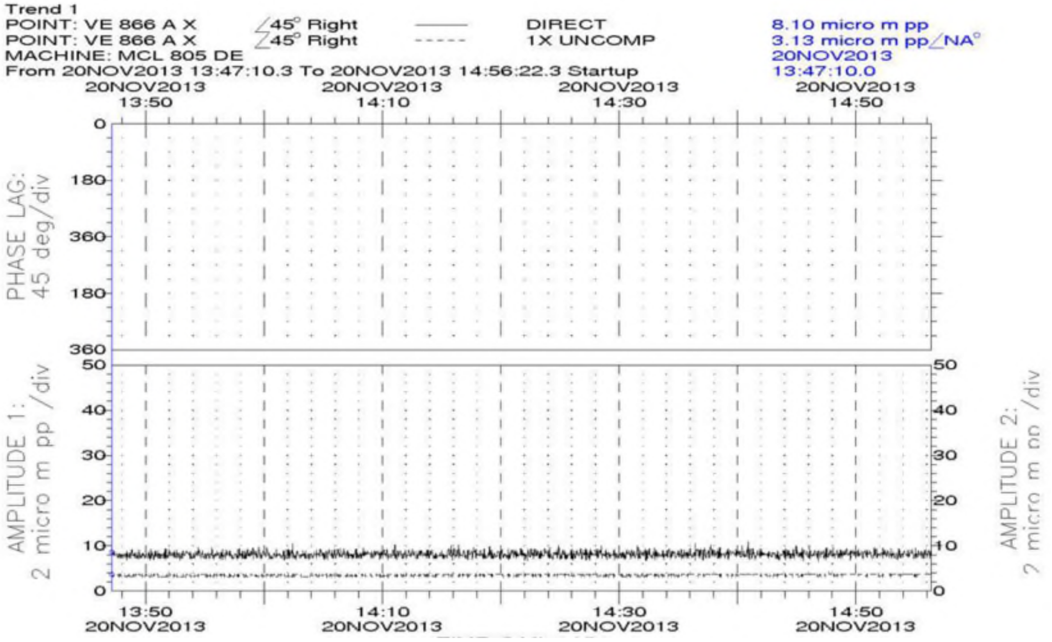

Figure 35 Low Pressure Methane Compressor: Steady State

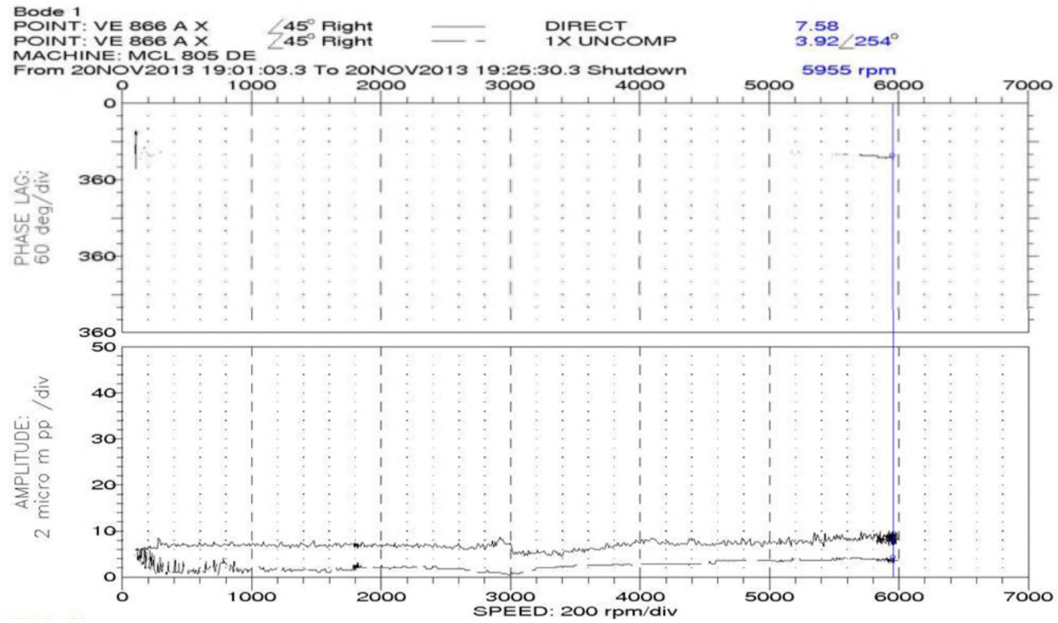

Figure 36 Low Pressure Methane Compressor: Shutdown

<u>Medium Pressure or Intermediate Pressure Methane Compressor (MCL 806)</u>:

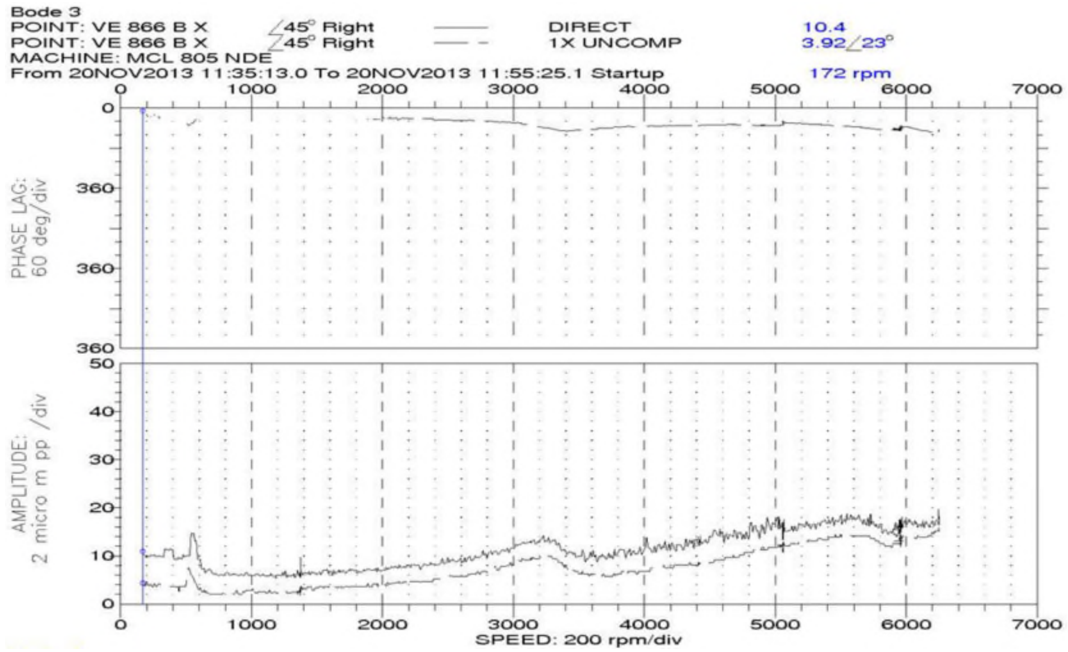

Figure 37 Medium Pressure or Intermediate Pressure Methane Compressor: Start-up

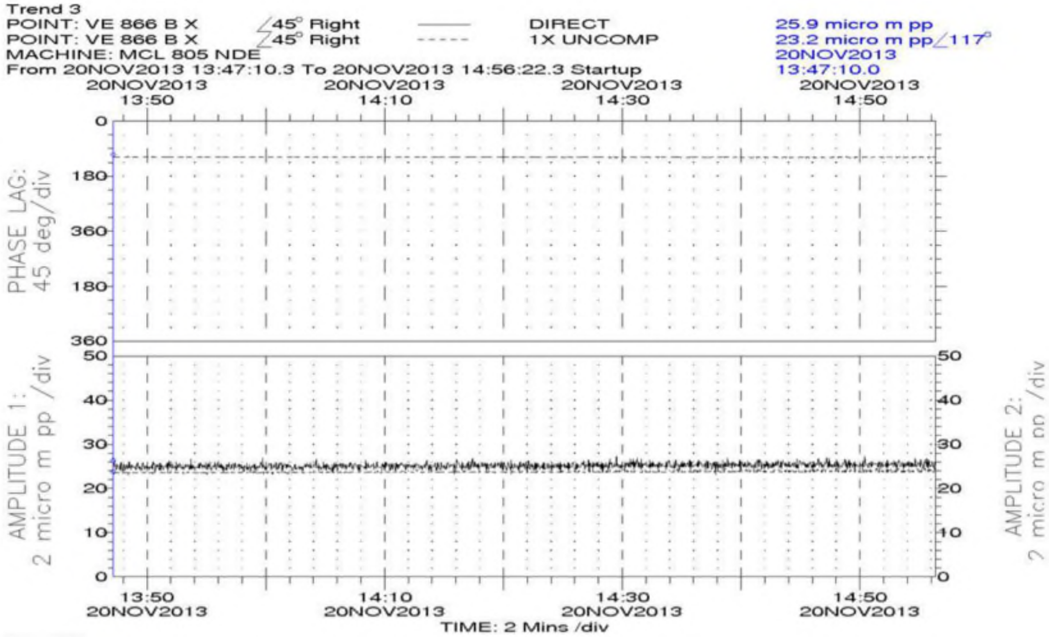

Figure 38 Medium Pressure or Intermediate Pressure Methane Compressor: Steady State

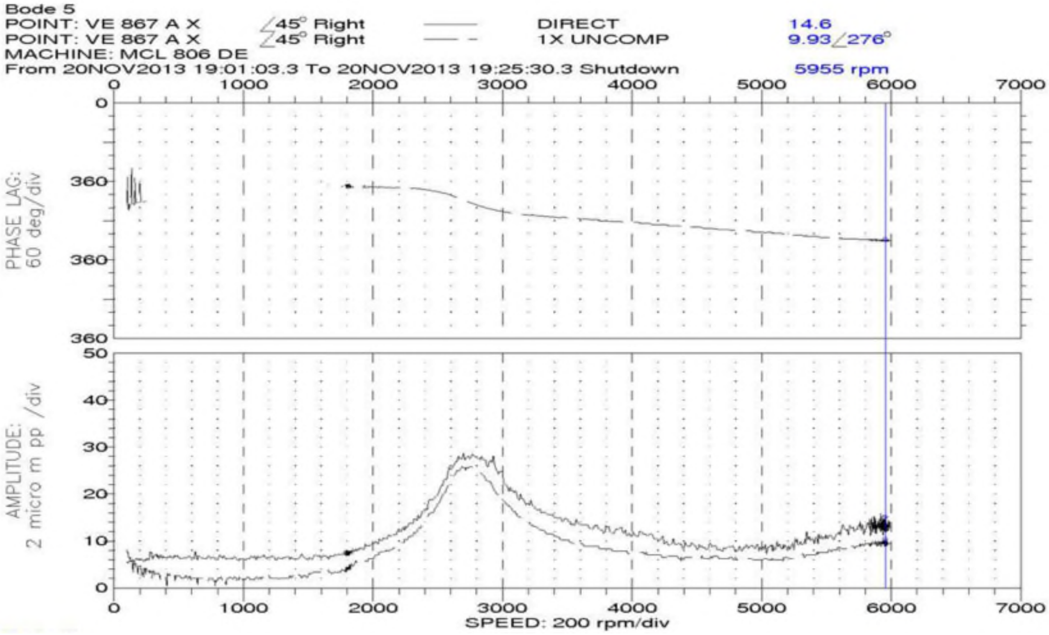

Figure 39 Medium Pressure or Intermediate Pressure Methane Compressor: Shutdown

High Pressure Methane Compressor (2BCL 608):

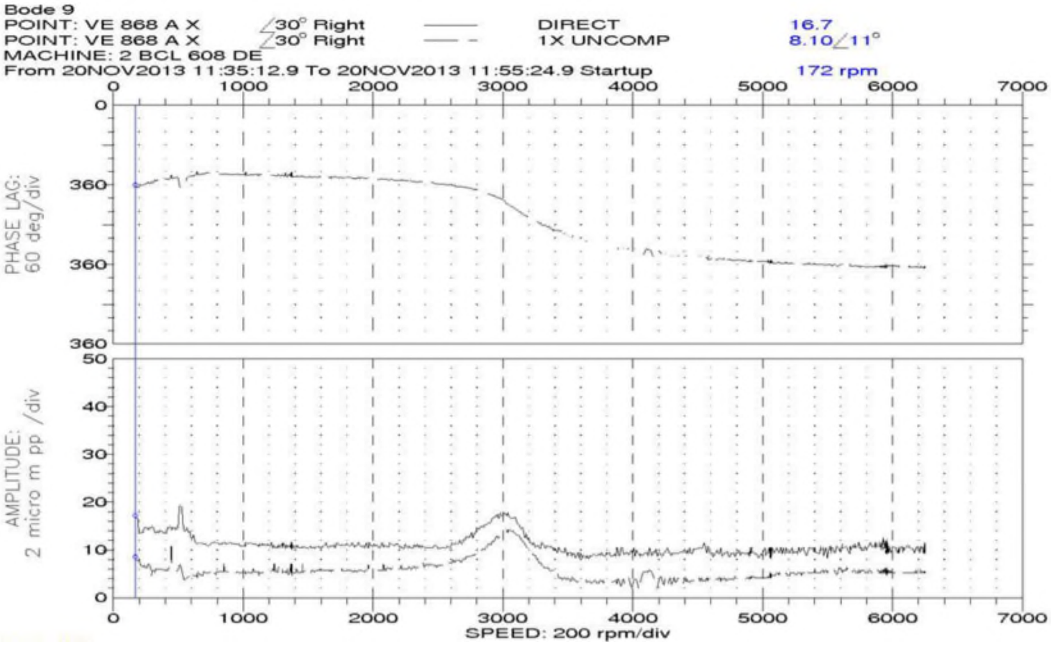

Figure 40 High Pressure Methane Compressor: Start-up

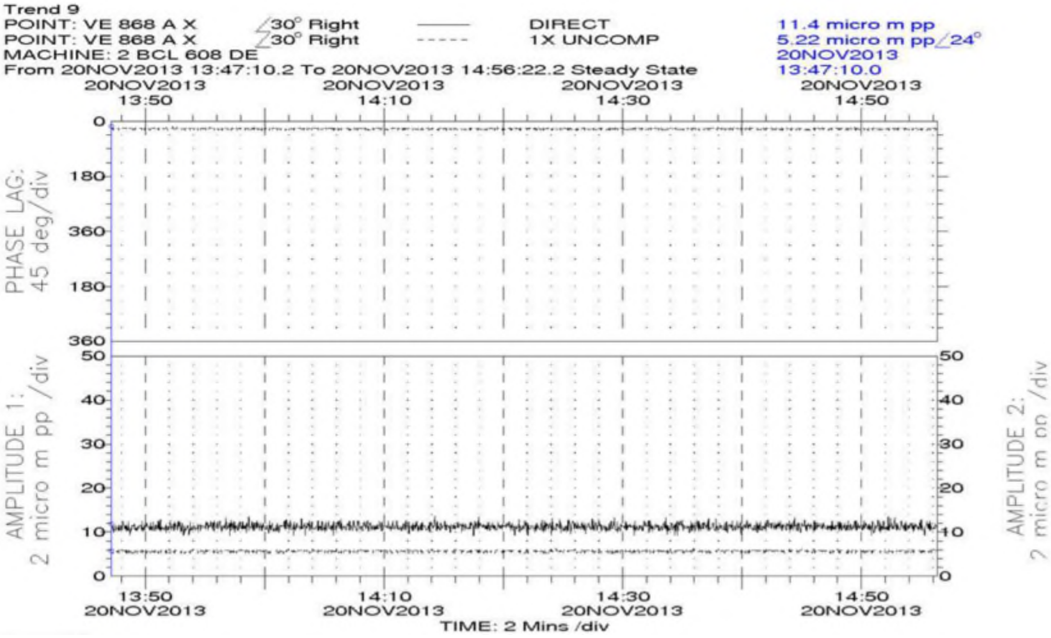

Figure 41 High Pressure Methane Compressor: Steady State

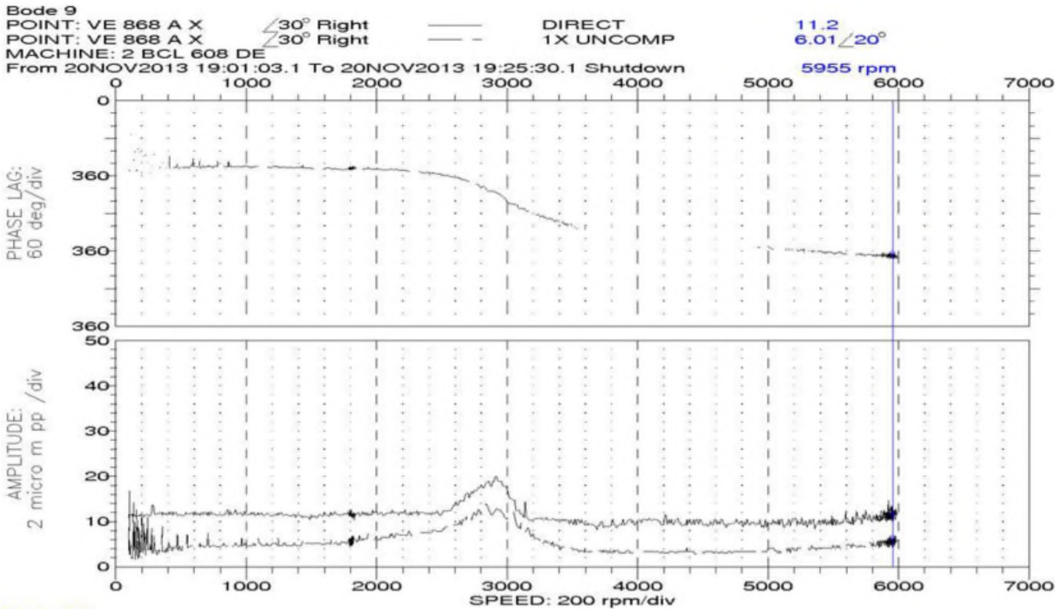

Figure 42 High Pressure Methane Compressor: Shutdown

Auxiliary Testing

Online Water Wash Systems

For Wheatstone, a fully automated online washing system was included to allow washing of 16 gas turbines daily without impact on operations. Testing of the on/offline water washing system was included to verify the correct implementation of the control logic and mechanical flawless test execution.

Demineralized water was used as washing solution for the off/online water wash. The offline water wash operation was initiated in remote mode from the Unit Control System (UCS). During the water wash procedure, the High Pressure Gas Turbine shaft was motored at 2,200 rpm and the Low Pressure Gas Turbine shaft at 349 rpm. While accelerating, the flow of wash solution to the water wash manifold can be initiated when the Low Pressure Gas Turbine shaft speed is 400 rpm. The duration of water-wash was 2,400 s (40 min), and then the sequence was ended.

The sequence was also repeated starting the operation from the water wash skid local button. The online water wash sequence was performed when the Gas Turbine was running and partially loaded. The sequence was also initiated in remote mode from the UCS and washing was performed for five minutes. Based on past history of other gas turbines, a static discharge condition could occur when water washing. This condition has occurred on machines with evaporative cooling. The variable stator vane bushings used for the LM6000 provide a grounding path for the vanes to prevent the buildup of static charge. To confirm this, the evaporative cooler was put in operation during the sequence to confirm there was no 'arcing' on the High Pressure Compressor Variable Stator Vane Bushings by visual inspection through the enclosure glass. All sequences were automatically managed by the MKIVe. All sequences were successfully, completely executed with no trip condition due to or during the On-Line Washing Sequence.

Inlet Filter and Evaporative Cooling Systems

There are four main sections in the inlet filter house.

1. Marine Vane Separator: Its main purpose is to catch rain droplets, trash, sand and debris.
2. Pulse Self-Cleaning High Efficiency (F9) Filter: The section serves the filtration of water droplets, dust, large size particles using synthetic and water resistant media.
3. Static HEPA Filter Section: This section provides ultra clean air to minimize impact to gas turbine performance.
4. Evaporative Cooling Section: This section contains an evaporating media through which treated or high-quality water is provided using pumps. The filtered air from the first three sections comes in contact with the very fine water droplets and these droplets evaporate thus cooling the inlet air by lowering its temperature. Drift Eliminator breaks down the droplets and drains the water back to the water tank. Basically, this process lowers the inlet air temperature and increases the mass flow to the gas

turbine axial compressor inlet. The evaporating media section was installed and tested during the string test. Because of the cold ambient temperature during string testing, the evaporative cooling water was not circulating during the majority of the string testing. The following psychometric chart shows the process graphically:

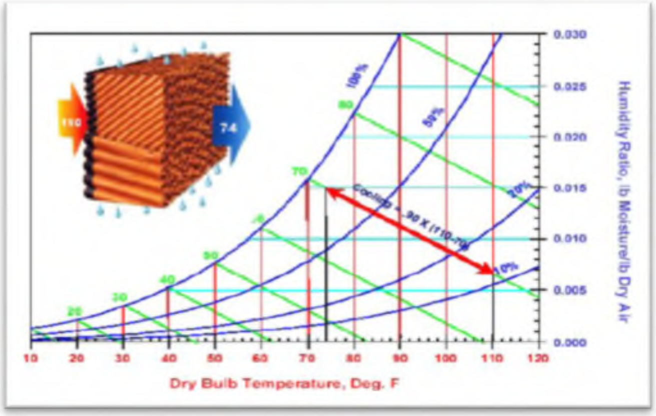

Figure 43 - Evaporative Cooling of the Gas Turbine Inlet Air

Pulse Jet Cleaning

This is a self-cleaning system capable of automatically cleaning the filter elements via a reverse pulse of air. This mechanism extends the overall life of the filter elements. When the filter element pressure drop reaches a particular value (clogged / dirty filter), the cleaning is initiated. Upon command from the automatic sequencing control, a solenoid-operated air valve directs a blast of high-pressure reverse airflow into the filters. This shocks and causes a momentary backflow through the filters, dislodging accumulated dust from the outside of the elements and allowing it to disperse. This operation was verified during the string test.

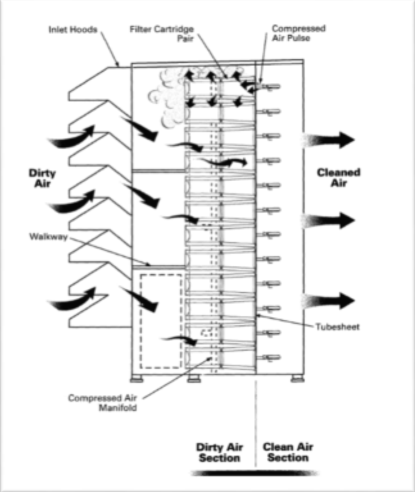

Figure 44 - Overview of the Low Stage Filter Section and Pulse Jet Cleaning

Validation of Sump Pressurization and Evacuation Systems

The most significant difference from the power generation to mechanical drive application is the speed of the LPC during the start sequence. For the power generation application, the only load during starting is the inertia of the generator. Power generation applications reach “sync idle” prior to warm-up with the LPC operating at 3,600 rpm. For the mechanical drive, the load from the process compressors results in the LPC operating at a low speed during the warm-up and acceleration phases of the start sequence.

In particular, low speed LPC operation during start up results in low sump pressurization pressure. Sumps pressurization is generated by LPC delivery pressure (P25). At low LP rotor speed P25 is low, and then the available pressure is not sufficient to assure proper sump pressurization. Low LP rotor speed is a normal potential operating condition in a Mechanical Drive (MD) train, while it is a transient condition in a Generator Drive (GD) train. During the MD train start sequence, the LM6000 requires sump pressurization and sump evacuation systems to ensure that the bearing sumps do not leak oil or ingest combustion gases respectively. By the time the LPC reaches the minimum operating speed of 3,240 rpm, sufficient sump pressures are developed that the sump evacuation and sump pressurization systems can be shut off and are not required during normal operation.

Hence, in order to keep the required airflow inward through the sump oil seal, a 'Sump Evacuation System (SES)' was designed to pull air through the oil vent creating a low pressure downstream of the vent. This represents one of the NPI (New Product Introduction) systems needed to run the LM6000PF as a mechanical driver.

The SES system (part of the synthetic lube oil vapor separator) is composed of:

- Stainless steel suction blower connected to the common vent discharge
- LV motor to drive the blower
- Voltage Frequency Drive (VFD) to vary the speed of the blower

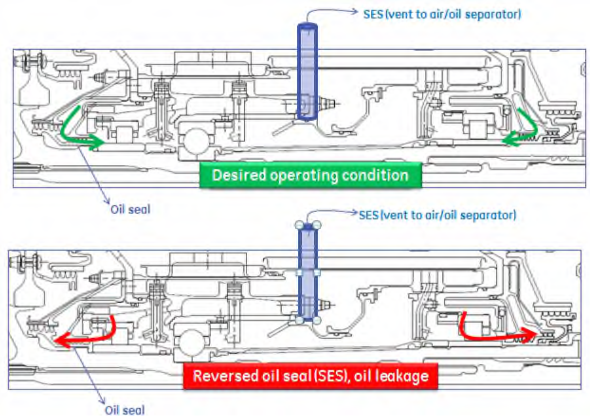

Figure 45 - Sump Evacuation System

In addition, low pressurization conditions (LPT shaft running at low speed during start-up conditions) can result in a flow reversal of the #4 and #5 air/air seals with a potential hot air (roughly equal to T3) ingestion into the sumps with a potential of catastrophic mechanical failures. OEM designed a second NPI auxiliary system, the Sump Pressurization system (SPS) for the B-C sump. This system, mounted directly on the side of the engine package inside the enclosure is composed of:

- A stainless steel blower
- A LV motor to drive the blower
- A Voltage frequency driver to vary the speed of the blower
- Additional piping supplied by OEM

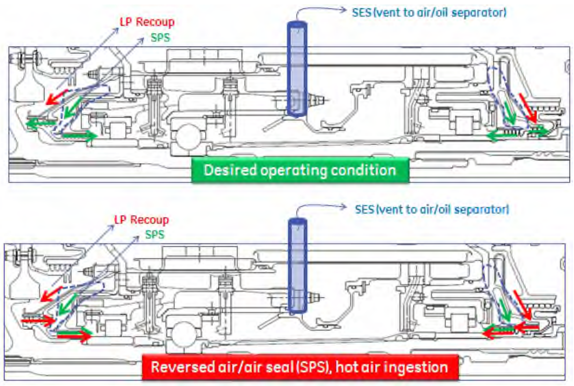

Figure 46 - Sump Pressurization System

Both systems are ON up to a certain LPT corrected speed:

- SPS ON if Corrected LPT speed < 2,400 rpm
- SES ON if Corrected LPT speed < 2,800 rpm

These NPI auxiliary systems were validated during the string test verifying the following conditions:

- Required pressure at LM6000PF interfaces within tolerance
- Validate control logics: ON, OFF, backup air
- Validate VFD setup
- Verify transient conditions

Turning Gear and Jacking Oil Systems

As mentioned previously, the Wheatstone LNG project utilized a double motor configuration (low/high) in conjunction with a jacking oil system on the gearbox and compressor journal bearings. Jacking oil system is designed to help the ‘turning gear (TG)’ system which is composed of two worm gear/low-voltage motor systems: first TG works for break-away torque, second TG for motoring during offline washing sequence and compressors cool-down (high-speed turning). In these operating conditions, the jacking oil is used to reduce the absorbed mechanical torque, keeping the turning gear, high-speed motor sufficiently small to avoid negative impacts on the compressors end sides (overhung weight / cones). High-speed turning is performed in order to avoid thermal bowing of the centrifugal compressors shafts after shut down or trip of a string.

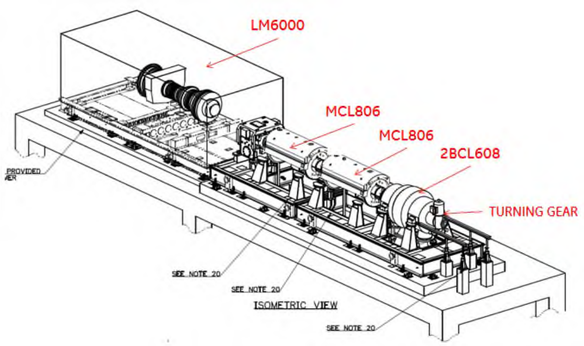

Figure 47 - Turning Gear System

The turning gear system together with the jacking oil system showed up the capability during string test to satisfy the design intent without overheating the LV motor during the cool-down test in the pressurized conditions (at SOP) and water-washing (offline) test, with measured average absorbed current roughly 70% of the motor rated current. In addition, the break-away capability of the low-speed motor exceeded the maximum break-away torque by around 11%.

CONCLUSIONS

The successful completion of string test was a significant milestone not only for the Wheatstone project, but also for the Original Equipment Manufacturer (OEM). There was no single trip of LM6000PF during the string test and the results were within the acceptable limits set for the test. One of the main purposes of the string test was to validate the ‘First of a Kind’ design of the LM6000PF as a ‘Mechanical Driver’ and it was satisfied by the successful string test. Also, the successful completion of the string test satisfied the plan put in place to counter the risks stated in the ‘Risk Mitigation Plan’ developed during the ‘Technology Qualification Process’. Last but not least, this successful string test provides a data point for OEM for the use of LM6000PF as a ‘Mechanical Driver’ on other LNG projects.

NOMENCLATURE

AMB = Active Magnetic Bearing
DLE = Dry Low Emissions
dP = Differential Pressure
EPC = Engineering, Procurement and Construction
FEED = Front End Engineering Design
FLFS = Full-Load, Full-Speed
FMEA = Failure Mode Effects Analysis
GB HSS = Gearbox High Speed Shaft (Pinion Shaft)
GD = Generator Drive
HP = High Pressure
HPC = High Pressure Compressor
HPT = High Pressure Turbine
LP = Low Pressure
LP = Low Pressure
LPC = Low Pressure Compressor
LPT = Low Pressure Turbine
MD = Mechanical Drive
MWI = Modified Wobbe Index
NDE = Non Driver End
NPI = New Product Introduction
OEM = Original Equipment Manufacturer
OMA = Operational Modal Analysis
PPM = Parts per Million
SES = Sump Evacuation System
SOP = Settle Out Pressure
SPS = Sump Pressurization system
T3 = High Pressure Turbine Inlet Temperature
TDS = Technology Development Stage
TNF = Torsional Natural Frequency
UCS = Unit Control System

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