STRAIN GAUGING OF ARATIATIA UNIT G3 GENERATOR ROTOR AND OTHER MPT NDT ACTIVITIES

Kevin J. Stevens[1,2] , Mike Myers [3], Aaron Worner[4] and Owen Cotton[4],

[1]k.stevens@mptsolutions.co.nz, MPT Solutions Ltd
PO Box 38-096, Lower Hutt, New Zealand 5045
[2]The MacDiarmid Institute for Advanced Materials and Nanotechnology,
P.O. Box 600, Wellington, New Zealand
[3]MPT Solutions PTY Ltd
PO Box 4551, Brisbane, Australia
[4]Mighty River Power, Mangakino, New Zealand

Abstract

The rotors at Aratiatia have historically experienced cracking during service. The strains on a cracked rotor have recently been measured using a UHF strain gauge telemetry system to determine the effects of operating conditions upon the stress levels, which are responsible for crack initiation and growth. The strains were monitored on the web and skirt of the rotor, during cold and warm starts, excitation and MVARS changes, changing power through the rough running range, and disruption of the vortex during synchronous conversion tests. Other NDT activities will also be discussed including MPT's involvement with the QUEST FTIS and LOTIS tube inspection systems.

1. Introduction

The rotors at Aratiatia are a 31 MW vertical Francis design, and have historically experienced cracking during service, serious enough to require replacement of the rotor on Generator G3. Recently discovered cracking in the G3 rotor which is <7 years old prompted an assessment of the cause of cracking and the preparation of a welding repair procedure. The assessment involved using strain gauges in november 2005 to determine operational stresses which can initiate and drive crack growth. These measurements can be used in a more sophisticated Finite Element based defect assessment if required [i]. Specifically the work requested by the Mighty River Power client, was required to address:

- Analysis of the stresses created in the areas of cracking (near the inner skirt – web welds).
- Identification of the load range of the machine where high stresses are produced.
- Identification of the frequencies causing these high stresses.

This paper describes the techniques used to achieve these aims, some of the results obtained and the conclusions that can be drawn.

MPT Solutions has recently been spun off and sold by Industrial Research Ltd (a NZ Crown Research Institute), to QUEST Reliability LLC [ii], a US based company specializing in NDT services to the Petrochemical, Energy and Aerospace Industries. A range of the NDT products developed by the new parent company will also be discussed.

2. Method

2.1. Equipment

The strain gauges used were the KFG-2-1K-C1-11L1M2R type from Kyowa. These are 1000 ohm gauges with a gauge length of 2.0 mm, pre attached leads, a gauge factor of 2.12 and thermal expansion coefficient compensation for low-medium carbon steel. 1000 ohm gauges were used instead of the more common 120 ohm gauges, to reduce current drain on the battery used to power the bridge circuit, providing greater electrical stability. The UHF telemetry system used was the Agile-Link software and the V-Link hardware available from Microstrain Inc [iii]. It consists of a basestation receiver (which is positioned on a girder over the rotor) connected to a laptop USB port, and a battery powered transmitter (positioned on the rotor) which provides excitation for the bridge strain gauge circuits. The wireless UHF strain gauge system can monitor a maximum of 4 strain gauge locations at a data logging frequency of up to 550 Hz on each channel, to a maximum buffer size of 65536 points. During operation the 65536 points are displayed on strip charts on a laptop, and can then be saved for later analysis. The typical operational rotation rate is 136 rpm (2.27 Hz), so approximately 242 measurements per channel can be recorded each rotation. The system was configured with 4 quarter bridge strain gauges, with internal bridge completion resistors. The gain and balance of the bridges can be changed remotely during operation to provide improved dynamic sensitivity within the range of the 12 bit analog to digital convertor built into the transmitter unit. The gauges were calibrated by recording the change in digitised signal in the UHF system caused by connecting a 270 k ohm resistor in parallel across the strain gauge. The calibration signal is equivalent to 0.174% strain.

The start time for each UHF data logging run is recorded in each stored data file and taken from a laptop clock. For improved synchronisation with the vibration analysis system of Connell Wagner and the Mighty River Power (MRP) SCADA system, MPT also logged the analog MW signal from G3 and the top X Proximity Sensor signal using a PMD-1608FS, 16 bit multi-channel USB data logger [iv]. The location of this proximity sensor is shown in reference [v]. A Visual Basic program was used to trigger and store data from the PMD system and record the laptop time. Typically a data logging rate of 100 Hz was used. The MRP SCADA system records the operating conditions and permanently mounted vibration proximity probe signals at 5 second intervals. In this paper, the time in seconds since midnight was used for plotting instead of the hours:minutes:seconds format in SCADA.

2.2. Strain Gauge Locations

The busbar has been repositioned away from the rectangular slot in the skirt, so that is passes above the skirt. During the weld repair of G3 in August 2005, the rectangular slot near web 11 was repair welded, removing a significant stress concentrator at the corner of the slot to which cracks had grown previously. During growth the crack curved around from the corners, until they were approximately parallel to the long edge of the slot, and encountered the top of the skirt [5, vi]. The skirt is a new feature in the present rotor added to stiffen the rotor, and was not on the old rotor design. When possible strain gauges were located near the previous sources of cracks, e.g. at the weld between the web and skirt at web 9. These were also repaired during the august shutdown. Figure 1 shows the two strain gauges that were placed in orthogonal directions on the skirt, in the circumferential and vertical directions at the height where the centre of the rectangular slot used to be at. To avoid any effects (due to dissimilar grades of material etc) of the weld repair of the rectangular slot, it was decided to strain gauge the skirt close to web 11, between webs 10 and 11.

Figure 1: Skirt gauges 3 and 4 near web 11. Gauge 4 is located 120 mm circumferentially from web 11, and 120 mm vertically down from the top surface of the skirt. Gauge 3 is located 10 mm below gauge 4.

Table 1: Strain gauge locations.

Gauge	Location	Orientation
1	Web 9	Vertical
2	Web 9	Radial
3	Skirt	Circumferential
4	Skirt	vertical

Two gauges, in the vertical and radial directions were located near web 9. It would not have been sensible to locate gauges directly on top of the weld as this is a region of stress gradients and the strain gauges have a large size relative to the weld. Also positioning gauges on welds would have required grinding into the weld, and this may in itself have initiated cracks. It is more sensible to place the gauges slightly away from the welds in uniform stress fields and use known stress concentration factors or a Finite Element model to calculate the likely stresses in the weld. A 3 wire lead configuration and screen was used on the strain gauge wiring to compensate for lead resistance and to provide improved immunity to radio frequency pickup. The leads were not earthed to the rotor, and were left floating relative to the battery voltage as experimentally this gave the best noise performance. Table 1 summarises the gauge locations.

3. Results

3.1. Strain Gauging

A test program was designed that consisted of running the rotor up to full speed, and varying excitation, power and MVARS, including cold and warm starts. Additionally synchronous conversion (SYNCON) tests were undertaken in which compressed air is blown into the draft tube to disrupt the rope vortex in water caused by the rotor. Multiple repeats and combinations of the above were achieved. Local control of the machine was used to keep the rotor within the rough running range for long enough for stable readings to be attained and synchronised with the operating conditions.

Some difficulties were experienced with signal cut outs, caused by lost communication with telemetry on rotor probably due to line of sight problems when the transmitter is rotated to be on the opposite side of the shaft to the fixed position receiver base station. Typically the system was triggered to stream data back to the laptop for 120 s, if communication was lost after 20 s, then the user has to wait at least 100 s until the transmitter unit finished executing the last commands it received and was available for streaming the next set of data back to the laptop. This signal cut outs required the test program to be designed so that test conditions were held for approximately 5 minutes at a time, so that a reasonable length file could be recorded.

The simplest initial analysis of the strain gauge waveforms is to calculate the mean stress and the stress range over 1 s intervals. The stress range is sensitive to noise spikes near the peaks so a more accurate approach is to curve fit a larger number of cycles, using Fast Fourier Transforms (FFT's). There is insufficient space to show all of the strain waveforms obtained, but examples are shown along with the main results.

Figure 2 shows that during a warm startup the peak circumferential stress is 24 MPa. This probably occurs when the water around the rotor is more turbulent than when the rope vortex is established. It is probable that the cracking seen initiated due to the starts. As the rotational speed increases to 136 rpm a mean circumferential tensile stress of about 20 MPa in the skirt and 8 MPa in the web above the stationary condition is produced.

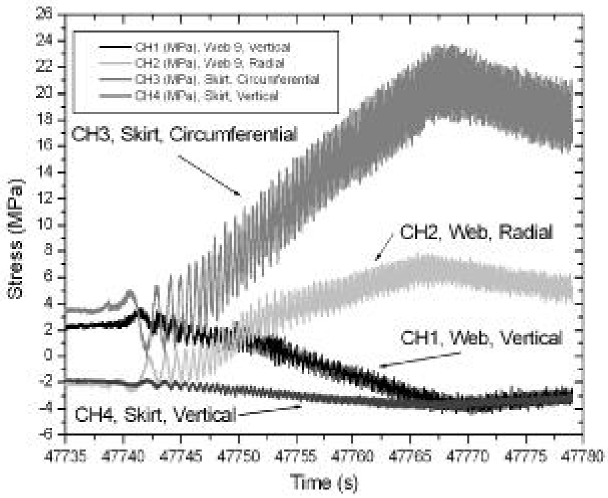

Figure 2.Warm rotor startup, 2.5 kV excitation.

The stresses are similar in the cold startups and warm startups. The proximity sensors are less sensitive to the 2nd and higher harmonic frequencies than the strain gauges. The largest tensile stresses were seen in the circumferential direction on the skirt. Tensile stresses were also observed in the radial direction on the web. The skirt has a higher level of circumferential or torsional stress than the radial or centrifugal stresses in the web.

Figure 3 shows that switching on the 11 kV excitation doubles the amplitude of the circumferential skirt stress waveform, but has less influence on the mean stress. The cyclic stress is more obvious on the expanded scale in Figure 3, than it was in Figure 2. The excitation tilts the axis of rotation and typically the proximity probes are used to calculate balance weights for the rotor in a compromise between mechanical (no excitation) and electrical (excitation on and at full load) balance. The Synchronous conversion test in which compressed air is blown into the draft tube to disrupt the rope vortex in the water caused by the rotor, showed that the vortex contributes to the 2nd harmonic frequency, but has a lesser effect than the excitation.

The MVARS specifies the inductive load, and can lead or trail the resistive load by 90°; during testing the MVARS was reversed through a 180° phase change. Switching MVARS from +15 to -15 makes the mean stress level of CH3 and CH2 less tensile, and the CH1 and CH4 signals more tensile. However the stress range is increased when the

MVARS is reversed to -15. Switching the MVARS has less effect than increasing the excitation from 0 to 11 kV.

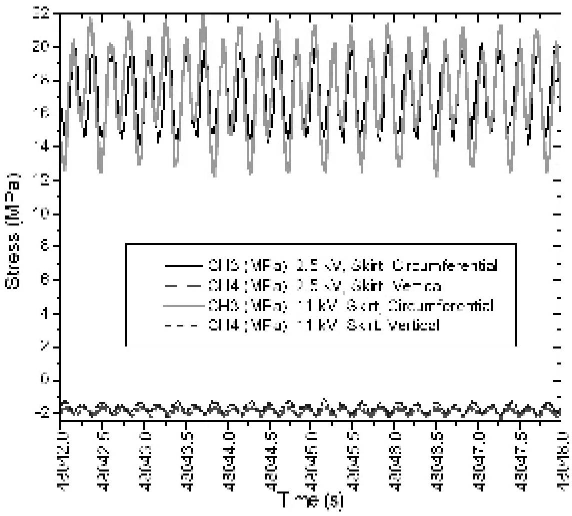

Figure 3: Changes in the waveform due to excitation.

Figure 4 shows how vibration in the rough running range from 5 to 18 MW increases the power in the 2nd, 3rd and 4th harmonics of the fundamental rotation frequency. The FFT power in the 2nd harmonic peaks at 10 MW. The 29 MW condition has the least stress at most frequencies. The dominant frequency was twice per revolution throughout the testing.

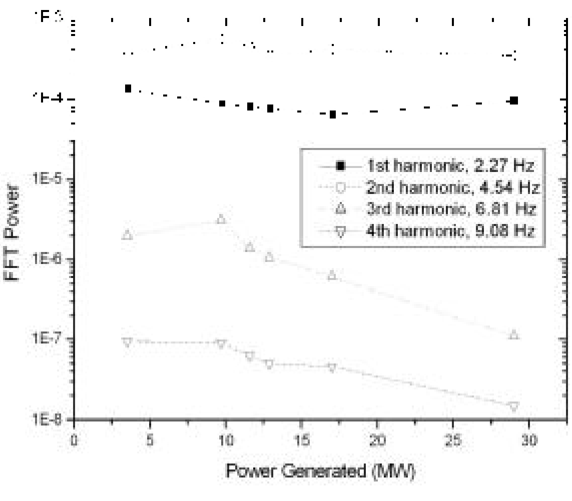

Figure 4: FFT analysis of the stresses on CH3, skirt circumferential gauge, as transit through the rough running range from 5- 18 MW.

The stresses measured by the gauges are small (<25 MPa), but the stresses at the welds will be much larger. The role of residual stresses at welds also needs to be considered in a defect assessment. At present a Finite Element Model has not been commissioned to predict stresses in the whole rotor as a function of operating condition. The most aggressive condition is during starts, and the number of starts is set indirectly by consumer demand and typically there will be 5 starts per day. The FFT's indicated that more power occurs in the 2nd harmonic and higher frequency vibrations through the rough running range, and this region of operation should be avoided, except when it is required to take the rotor up to full power.

3.2. Fired Heater Inspection Services

Quest's Furnace Tube Inspection System (FTIS) uses ultrasonic transducers mounted on a pig to detect and quantify wall thickness, diameter, corrosion, erosion, pitting, creep strain, swelling and bulging in serpentine piping coils. It travels at a nominal speed of 0.6 m/s through 102 to 203 mm coiled piping. It is flushed through with water which provides propulsion and ultrasound coupling. Figure 5 shows how graphical data analysis packages are used for plotting the inspection data.

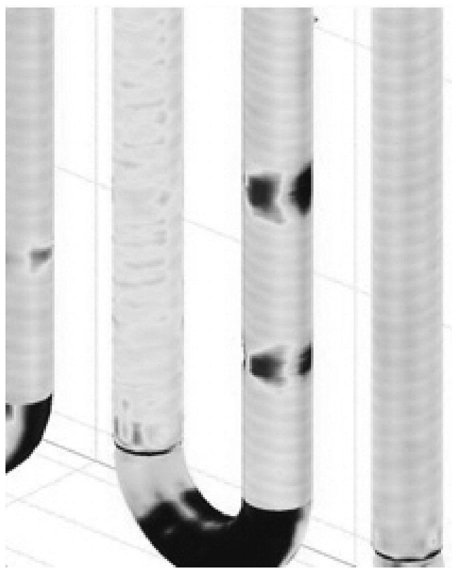

Figure 5: Typical graphical display of FTIS inspection data.

3.3. Laser Spiral Scan of Coke Drums

Delayed coking units are increasingly being used to process heavier crudes into lighter fractions for refineries. The severe heating and quenching rates in coking units much reduces the lifetime below that of other pressure vessels operating at relatively constant conditions. The difference in yield strength of welds compared to plate material, creates bulges after thermal cycling [vii, viii]. Quest have developed a laser distance measurement system mounted to a tensioned cable, positioned vertically inside a coke drum. The device is rotated and lowered to scan the inside of the coke drum to quantify coke drum bulging in order to optimize coker operation, with results being obtained like those shown in Figure 6.

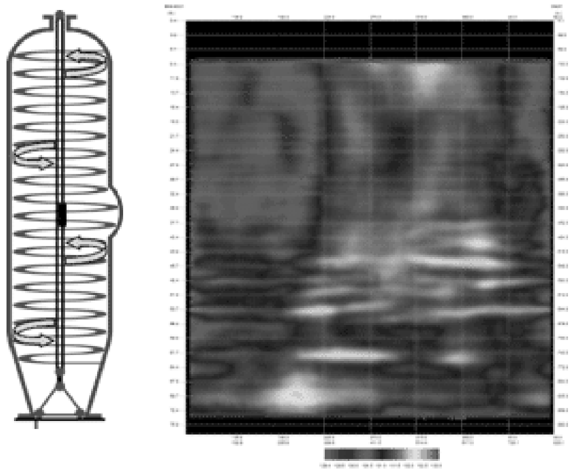

Figure 6: Coke drum spiral laser scanning system and 2d plot of inspection data.

3.4. LOTIS Steam Reformer Tube Inspection Services

Steam reformers are used in ammonia, methanol, hydrogen and gas process plants. Creep is the primary failure mechanisms at the high temperatures and pressures in the catalyst tubes. The Laser Tube Inspection System (LOTIS) is used to detect and quantify creep strain damage as shown in Figure 7. Quest have internal (if the catalyst is being replaced) and external tube inspection systems and crawlers (Figure 8). MPT has creep testing facilities and databases for converting LOTIS results into remaining life estimates.

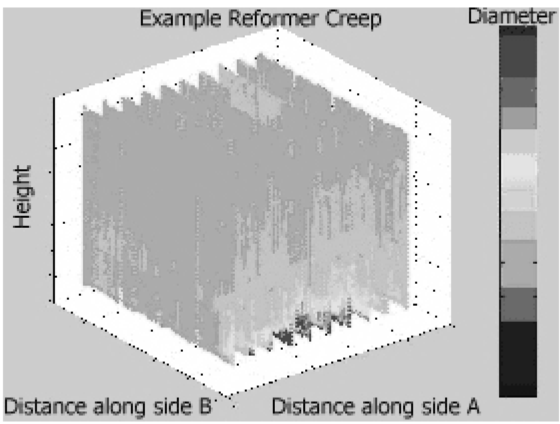

Figure 7: Typical LOTIS inspection results showing creep strain.

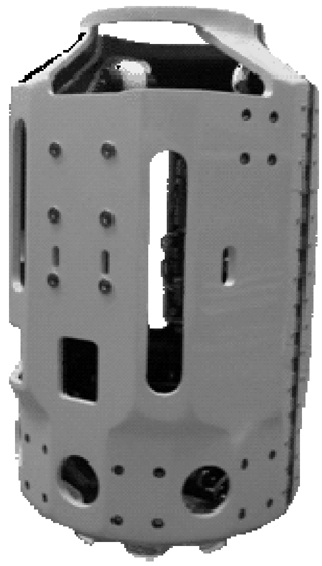

Figure 8: LOTIS external tube crawler

4. Conclusions

Extensive UHF strain gauge measurements collected on the G3 rotor at Aratiatia have been briefly summarized. The testing quantified the stress changes occurring during cold and warm starts, the transition through the rough running range and changes in excitation and MVARS. The largest stress changes are during cold starts. The excitation has significant effect of the stress range in the skirt but not the mean stress levels.

A range of NDT systems developed by Quest have been briefly summarized. A specialty is in laser based systems for sizing reformer tubes and coke drums. An ultrasonic pig system is used for steam piping inspection. MPT's expertise in metallurgy and corrosion is increasingly being used to predict the remaining life of plant components that have been inspected using the Quest NDT systems, combined with traditional techniques such as surface replication, hardness measurements and strain gauging.

5. Acknowledgements

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analysis. Mighty River Power for permission to publish this paper.

6. References

i. J. Wilson, A. Karstensen and D. Firth, "Fitness for purpose of the Ohau A G5 rotor arm with known propagating defects", 11th Hydro Power Engineering Exchange, Taupo, 2004.

ii. http://www.qi2.com/ and http://www.questtrutec.com

iii. http://www.microstrain.com/wireless-sensors.aspx

iv. http://www.mccdaq.com

v. R. Munn and D. Krippner, "Aratiatia G3 – A 30 MW, 136 RPM Accelerated Fatigue Test Rig", HPEE2000 Paper.

vi. NDT reports showing crack locations.

vii. R.S. Boswell and T. Ferraro, "Remaining Life evaluation of coke drums", Plant Engineering, Design and Responsibility Symposium, Energy Engineering Conference, 1997.

viii. J.A. Penso, Y.M. Lattarulo, A.J. Seijas, J. Torres, D. Howden, C.L. Tsai, "Understanding failure mechanisms to improve reliability of coke drums", ASME, 1999.