# FLATNESS SURVEY AND CORRECTION OF TURBINE-GENERATOR ALIGNMENT USING LASER MEASUREMENT TECHNIQUES

Michael A. Robinson[1] and H. Brett Houston[2]

[1, 2] ProGen Ltd, 2/829 Heaphy Terrace, Hamilton, New Zealand 3240

michael@progen.co.nz   brett@progen.co.nz

**Keywords:** *Geothermal, Turbine, Casing, Misalignment, Sag, Flatness, Laser, ProGen.*

## ABSTRACT

Turbine-Generator sets must be flat and correctly aligned to function reliably. The units are aligned when the plant is constructed, but they do not always stay that way. The plinth and foundation that supports the turbine and generator can twist and sag over time. This deformation can result in distortion of turbine casings and misalignment of the units. Many plant operators are not aware that this can and does happen. These conditions can result in a number of (often costly) flow-on effects. We aim to demonstrate in this paper that laser measurement has proven to be an integral part of the diagnosis and solution of these conditions. Turbine owners and operators stand to benefit from solving these issues through reducing unplanned downtime and costly repairs, and increasing performance.

## 1. INTRODUCTION

Turbine-Generator (TG) sets are commonly installed on a raised plinth structure as per the power station design. The TG set will consist of a turbine connected either directly to a generator, or through a reduction gearbox. A condenser is often installed underneath the turbine, inside the boundary of the plinth. The combined units of the TG set can be very heavy, often 500 tons or more. Additionally, the condenser may apply extra downward force to the turbine, due to the vacuum present when the machine is operating.

So, the foundation must be able to support the combined weight of the plinth structure, the TG set, and additional loads imposed by condenser vacuum. The plinth must also absorb, without permanently deforming, significant twisting forces implied to it while the set is generating under load. Thus the design and construction of both the foundation and the plinth is very important. The intention is for all components to be adequately supported, and all original installation dimensions to be maintained throughout the operating life of the power station.

In practice, this is rarely the case. Foundations and turbine plinths typically move and distort to some degree over time, due to foundation subsidence and/or inherent flexibility in the plinth structure. The amount, and rate, of movement will depend on the particular design considered. In one power station in New Zealand the turbine plinth had begun to deform immediately following construction, as the concrete cured. Another station suffers from a flexible plinth; the turbine bows by up to 1.5mm during operation, due to the condenser vacuum acting on the turbine.

## 2. PROBLEMS ARISING FROM FOUNDATION/PLINTH MOVEMENT

During installation of a TG set, all the components are carefully positioned relative to one another, and according to tight design tolerances. The turbine diaphragms and glands are positioned concentrically within the casings. There are typically very small clearances between these stationary components and the rotor/s of the turbine; tight clearances minimise steam leakage in these areas.

As the foundation and plinth settle and move during the life of the machine, the points at which the machinery rest on the plinth may also move. This can result in a change in the relationship between separate units of the TG set. It can also result in twisting and sagging in sections of large cast/fabricated steel structures, such as turbine casings.

Broadly speaking, two issues are commonly encountered:

- Shaft alignment between the separate units of the set may move outside specification
- Turbine casings twist and sag, potentially leading to rubbing between the rotor and stationary components, and erosion, in steam sealing areas

Distortion of the casing can result in contact between the rotor and the stationary sealing elements. If there is contact, or even reduced clearance in sectors of the steam seals, there will likely be increased clearance in the opposing sectors. Increased quantities of steam and entrained water bypassing seals in these areas often results in accelerated erosion of both the seals and the parent metals[1]. Repairs to sealing elements that are damaged by either rubbing contact or erosion can be costly. Increased steam seal clearance will also result in reduced turbine performance.

Changes in the shaft alignment of the units may result in uneven loading of the rotor bearings. Some bearings may become over loaded, some under loaded. Over loading bearings can increase the operating temperature, and potentially lead to failure. Bearings that run below the designed loading are a possible source of vibration. Misaligned rotors may also cause difficulty in fitting and removing solid coupling bolting. In extreme cases rotors have experienced fatigue failure after operating misaligned for extended periods.

## 3. IDENTIFING THE ISSUES

There are a number of ways in which movement and distortion of plinths and turbine casings can be identified, apart from measuring the flatness of the casing. The 'bigger picture' should be kept in mind when arriving at diagnoses and weighing up solutions. Many measurements and phenomenon must be considered, both prior to, and during, a turbine strip down, to arrive at the correct diagnosis and formulate a practical solution to the issue.

It is very important to consider past overhaul inspection records (if they exist). These records may help with identifying long term trends, and enable tracking of movement and deformation. Records may also contain information about previous attempts to mitigate the effects of distortion or subsidence, which may need to be reversed. In one instance a particular casing had sagged in the centre to the point that the overhaul team were using angle grinders to open out the top of the diaphragm location spigots, giving enough clearance for the diaphragms to be aligned correctly. This reinforces the need to carefully collect and study a variety of information about the machine, and avoid tunnel vision.

The facets of the machine which tend to indicate plinth or casing distortion are detailed as follows:

### 3.1 Embedded Plinth Measurement Points

Often there are machined steel reference measurement points embedded into the concrete TG plinth structure. These are used during construction of the TG and should be measured periodically using an optical or laser device. Measurements are able to be undertaken while the unit is operating, and can directly indicate whether the plinth is distorting. In addition, baseline measurements that are taken while the unit is generating under full load can be compared with a series of other measurements taken under varying conditions such as:

- Unloaded, under vacuum
- Shut down, no vacuum
- Various stages of disassembly

In this way, the effect of each of these factors on the plinth can be assessed, and later allowance made during remedial works.

### 3.2 Shaft Alignment

Changes in the attitude of the turbine rotor/s relative to each other, or to the generator rotor, may be observed as changes in the shaft alignment measurements. The changes may be trended over time, as alignment measurements are undertaken at key maintenance service intervals.

### 3.3 Thrust Bearing

Sag occurring in the centre of the turbine casing can result in uneven contact, and loading, of the turbine thrust bearing; depending on the design. The TG set detailed in the following case study features integral bearing pedestals. This feature causes the top of the thrust bearings to tilt inward as the casing sags toward the centre. The total axial float of the rotor is therefore reduced; and evidence of hard contact is visible on the thrust pads in specific areas, since fewer pads are now supporting the load.

### 3.4 Internal Seal Clearances

Diaphragms are positioned concentrically within the casings. Thus if the casing is flat, and not twisted or sagged, the centres of the diaphragms will form a straight line. It is important that the diaphragms are centred precisely about the rotor, as there are a number of steam sealing elements that rely on tight clearances between the turbine rotor and the diaphragms.

It is important to study past records of seal clearances, as as-found measurements can indicate movement of the casing. The diaphragms are typically positioned using a combination of step height, and seal bore alignment (laser or tightwire) measurement. Bore alignment measurement will allow some correction for casing distortion to be made. If step height measurements alone are used for set-up, correct diaphragm bore alignment probably has not been achieved, especially if the casings are not flat.

### 3.5 Diaphragm Half Joint Erosion

Erosion of the diaphragm half joints can indicate that they are not sealing correctly when the casings are closed up. This can occur when diaphragms are positioned within a distorted casing to achieve better seal clearances. It is difficult to position the upper diaphragm halves to reflect the position of the lower halves, and achieve satisfactory bore alignment when the machine is assembled. Again, laser or tightwire bore alignment techniques are crucial to achieving a good result in this area.

### 3.6 Shaft Levels

One of the measurements commonly recorded during machine overhaul is shaft levels. A machine level is placed on the rotor bearing journals and a reading taken. The level measurements will have been recorded when the machine was first assembled and hence can be used for comparison. Changes in the shaft levels can be considered in conjunction with shaft alignment figures, to determine a more detailed picture of any distortion and/or movement.

### 3.7 Erosion Patterns

If the casing has distorted and altered the relationship of the diaphragms to the rotor, steam seal clearances may be affected. If the seal clearances become larger, increased quantities of steam and entrained water can cause accelerated erosion[1]. These patterns should be studied and related to the as-found seal clearances.

### 3.8 Casing Joint Gap

Any clearance between the upper and lower casing half joint surfaces can be measured after the upper casing is unbolted. If the lower casing has distorted or sagged it may result in increased clearance. It is important to note that upper casings may have some inherent twist due to fabrication, stress relief etc.

If the gap is large and the upper casing is a reasonably strong structure, the gap may not close adequately when the joint is bolted. The tension applied to the bolting is partly used to bend the upper casing to conform with the lower, thus decreasing the pressure applied to the closed joint to seal it. In extreme cases bolting must be overtightened simply to close the half joint gap. Even if the casing half joint gap is closed, a gap may remain internally at the diaphragm half joints. A gap in this region may exacerbate diaphragm half joint erosion as a result of steam leakage.

## 4. MEASUREMENT OF CASING FLATNESS

Laser flatness measurement of the lower casing half joint will convey the magnitude of the casing distortion directly to the technician. It is fast and simple to carry out and provides a cost effective option when compared to other techniques. After considering the measurement results in conjunction with other information gained about the TG, a decision can be made on the most effective and practical corrective action to be taken. Repeating the measurements post remedial work can verify the effectiveness of the corrective actions.

### 4.1 Set Up

ProGen uses the Easy-Laser measurement system to evaluate casing flatness. The unit consists of a laser beam transmitter, and a laser beam detector. The transmitter features a swivelling head that enables the laser beam to be projected over and above the complete surface of the casing. The area swept by the laser beam is known as the reference plane. The detector is mounted on a magnetic base via posts; and is placed by the operator at various locations on the turbine casing joint surface.

A plan drawing of the turbine lower casing is made. The locations on the casing joint surface that will be measured are marked on this drawing. Axes x and y are assigned to the turbine casing, then each of the measurement locations is assigned a set of coordinates in terms of x and y. The coordinates relate the real measurement position to the virtual position that is created within the Easy-Laser display unit.

The transmitter is preferably placed at one of the corners of the turbine casing half joint. If this is not possible, then it should be in a position where the laser beam can be projected over the whole of the casing joint surface. The transmitter is referenced to the casing surface using 3 points. Two of these are at the extremes of the x and y axes, and one is as close as possible to the base of the transmitter (in either axis). The objective when referencing the transmitter is for the laser beam to contact the detector at the same vertical position, at each of the three points chosen for referencing.

This results in the laser beam sweeping through a flat plane that lies a certain distance above the casing half joint surface. This plane will be parallel to another plane lying on the three points of the casing that were used for transmitter referencing. It is not usually necessary to consider true level when conducting casing flatness measurements.

### 4.2 Measurement

The detector is placed at one of the measurement points. The head of the transmitter is swivelled until the laser beam is detected. A height measurement is registered, then the detector is moved to the next measurement position. Following measurement of all the positions, the results are displayed on a drawing created for that purpose.

### 4.3 Limitations

The laser beam and detector have a theoretical resolution of $0.001mm^2$. The system has a practical accuracy of 0.01mm. Some environmental conditions affect the accuracy of the system, largely temperature gradients affecting the straightness of the laser beam. These include:

- Radiated heat from running or recently running machinery
- Air currents from condenser ventilation
- Air currents through building ventilation
- Radiated heat from sunlight acting on steel clad buildings
- Vibrations coming from running machinery

Some of these circumstances can be mitigated in various ways, however due to other factors it is not always possible. In these cases it is up to the Easy-Laser operator to ensure they recognise when some inaccuracy may exist, and either take this into account when decisions regarding corrective actions are made, or ensure this is communicated to the necessary persons.

## 5. TG CASE STUDY

During 2015 the authors participated in the overhaul of a 147MW geothermal TG at Nga Awa Purua. The turbine features large fabricated steel casings, with integral bearing pedestals. The lower casing rests on the TG plinth on a series of shim packs ranged around the perimeter of the casing. There is a void, or unsupported section, in the centre around the turbine cylinder. The lower casing has an inclination to sag toward this unsupported centre. The weight of the condenser and the vacuum applied by it to the casing may also contribute to this tendency. The casings may also change attitude relative to the generator due to plinth movement.

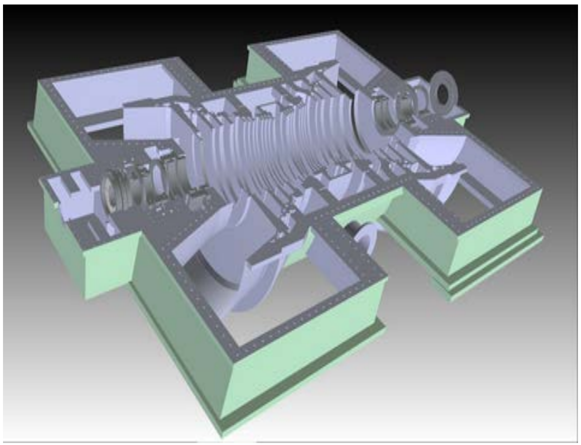


**Figure 1: Representative Image of Lower Casing.**

Studying information recorded during past overhaul of the TG revealed that plinth movement, and subsequent distortion of the turbine casing, may have been occurring. The unit was scheduled for overhaul during July-August 2015; providing an opportunity to ascertain the presence and extent of these issues, and realign the TG if necessary.

Various measurements and information regarding the as-found state of the TG were collected during the strip down process. This information was reviewed by technical staff, including those from ProGen, with the object of deciding how to correct the defects. A summary of the information used in the decision making process follows.

### 5.1 As-found Shaft Alignment of TG

As-found shaft alignment measurements showed that: the turbine coupling hub was higher than the generator hub by 0.07mm, and the coupling gap was open at the top by 0.07mm; against targets of 0.00mm. The coupling gap figures, regarded alone, would seem to indicate that either the front of the turbine or the rear of the generator should be raised by approximately 0.5mm to correct this gap. Lifting the front of the turbine would partially correct the height offset of the turbine coupling hub; whereas lifting the rear bearing of the generator would exacerbate that issue, and require lifting both front and rear generator bearings significantly.

Previous inspection records showed that realignment of the TG had been conducted during past overhaul work, so these measurements were only be used for an indication of the as-found state of the unit. Calculations for final shaft alignment adjustments were based on measurements conducted after the turbine casing had been shimmed.

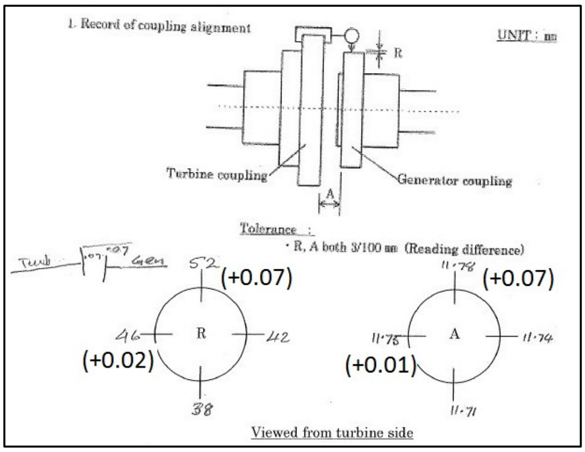



**Figure 2: As-Found Shaft Alignment**[3]

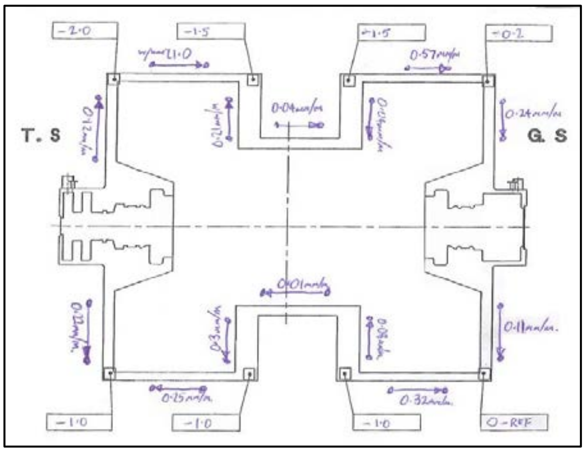



**Figure 3: Optical and Spirit Level Measurements** (3)

### 5.2 Turbine Rotor Level Check

Placing a machine level on each of the turbine rotor bearing journals showed that:

- The rotor was low at the #1 bearing end
- #1 bearing journal was at an angle of approximately 0.12mm/m
- #2 bearing journal was at an angle of approximately 0.70mm/m

Assuming that the rotor was at an average angle of 0.55mm/m and that the rotor is about 6 meters between journals, this indicated that the #1 bearing journal could be about 3.3mm lower than the #2 bearing journal.

### 5.3 Thrust Bearings

The thrust bearings showed minor thermal ratcheting on the lower inner, and upper outer, sectors. Total rotor float was 0.19mm, against a design tolerance of 0.25 – 0.39mm. These symptoms were consistent with a depression in the centre of the casing. The depression causes the #1 bearing region of the casing to twist down toward the centre of the unit; causing reduced rotor float, and hard contact in the two sectors of the thrust bearings that showed signs of thermal ratcheting.

### 5.4 Optical Level Measurement of Turbine Casing

Since the turbine casing was initially set up level at the time of installation, it was decided to check the attitude of the casing using an optical level. This was carried out after the top casing and rotor were removed. This information would then assist in deciding how to correct the shaft alignment issue.

The measurements taken with the optical level indicated that the left front corner of the casing was lower than the right rear by about 2mm. Spirit level measurements showed that the area of #1 bearing could be even lower.

### 5.5 Laser Measurement of Casing Flatness

Laser measurement of the flatness of the lower casing allowed many locations on the casing to be rapidly measured. Measurement positions were chosen based on the location of shim packs, and key components of the machine. Adjustments in specific locations could be optimised based on this information.

The laser transmitter was referenced off three corners of the turbine casing; flatness measurements were then conducted.

The measurements showed that a general bow shaped depression existed along the length of the casing. The maximum depression was in the region of the centre right of the casing with approximately 1.2mm maximum magnitude.

There was also a depression along the width of the front of the casing in the region of the #1 bearing, with approximately 0.6mm maximum magnitude.

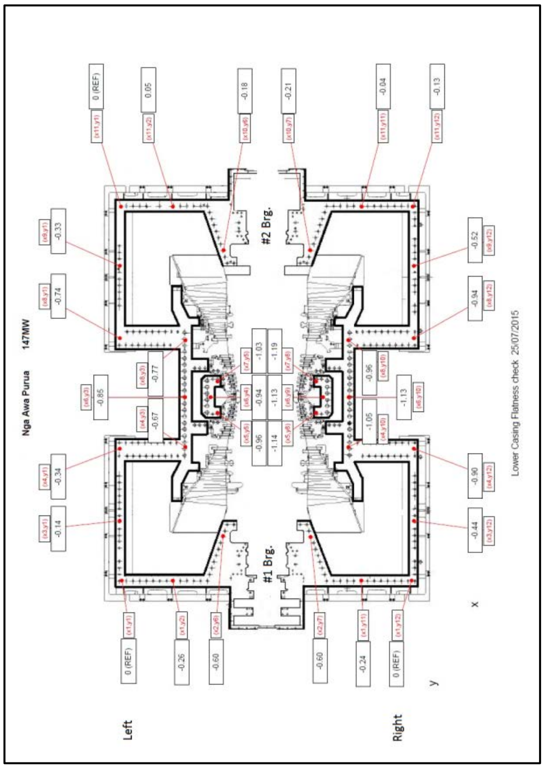



**Figure 4: As-Found Lower Casing Flatness**[3]

The current method used to set the diaphragm heights is to adjust them level with the half joint face of the casings. This method assumes that the casing is flat and level. So, considering that the internal seal clearances are in the order of 0.3 – 0.4mm, it is clear that with a depression of up to 1.2mm along the length of the casings there was a high risk of diaphragm seal contact with the rotor.

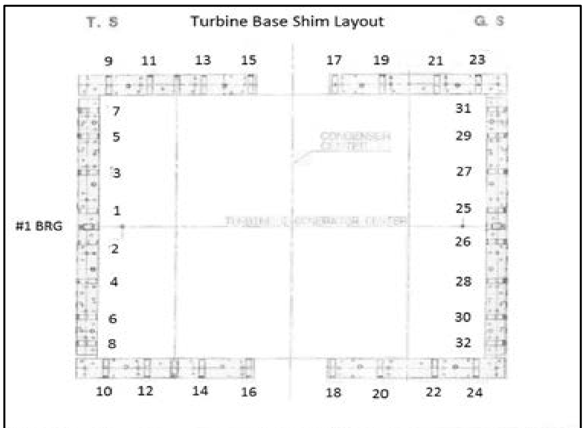
### 5.6 Correction of Turbine Casing Flatness and Level

The information that has been summarised in the preceding paragraphs was carefully reviewed by technical staff representing the owner, the manufacturer, and ProGen. Corrective actions to be undertaken were officially prescribed by the manufacturer's representative.

It was decided that the turbine lower casing would be shifted nearer to true level, and that the depressions would be flattened out simultaneously. This would be achieved by lifting the left front of the turbine by about 2mm, and the right front by about 1mm. The rear corners would not be disturbed.

The casing design incorporates shim packs, for the purpose of levelling the casing. These packs can easily be accessed and altered. Once the extent of the alterations was decided, the changes were carried out. The casing flatness was then rechecked with the Easy-Laser.

The changes to the shim packs in the positions along each side were calculated according to their location relative to the front and rear corners, and the shim changes made at the front corners. Added to this base alteration is the need to flatten out the depressions in the casing; so extra shim thickness was factored into the calculations for the positions in the centre regions of the sides.




| No | As found pack | Add | As left pack | Total |
|---|---|---|---|---|
| 1 | | 2.0 | ·85 ·65 ·65 ·95 ·5 ·5 ·2 | 4·26 |
| 2 | | 2.0 | 1, ·5 ·5 ·2 ·85 ·65 ·65 | 4·3 |
| 3 | 1, ·5 (·5) ·2 ·1 ·05 | 2.0 | ·85 ·85 ·65 | 4·35 |
| 4 | 1, ·5, ·5 (·1)(·1)(·1)(·1) | 1.7 | ·85 ·85 ·65 | 4·1 |
| 5 | | 2.0 | | |
| 6 | | 1.3 | ·65 ·65 ·5 1·0 ·5 ·1 ·2 ·2 | 3·73 |
| 7 | 1, ·5, ·5 (·1)(·1)(·1) | 2.0 | ·85 ·85 ·65 | 4·4 |
| 8 | | 1.0 | ·1 ·2 ·2 ·5 ·5 1·0 ·2 ·65 | 3·3 |
| 9 | 1, ·5 ·5 ·2 ·1 ·04 | 2.0 | ·65 ·65 ·65 | 4·4 |
| 10 | | 1.0 | 1 ·05 ·5 ·1 ·2 ·2 ·5 ·5 ·5 | 3·6 |
| 11 | 1, ·5, ·5, ·2, ·2 | 2.0 | ·65 ·65 ·65 | 4·4 |
| 12 | | 1.2 | ·5 ·2 ·1 ·1 ·05 ·98 ·5 ·2 ·5 ·5 | 3·6 |
| 13 | 1, 1 ·25 ·2 ·1 ·1 | 2.0 | ·85 ·85 ·2 | 4·4 |
| 14 | | 1.6 | ·5 ·5 ·5 ·2 1·0 ·65 ·1 ·85 | 3·8 |
| 15 | ·5, ·5 1·0 ·1 ·2 ·2 ·04 | 1.8 | ·85 ·85 ·05 | 4·3 |
| 16 | | 1.8 | | 4·25 |
| 17 | 1, ·2 ·5 ·5 | 2.2 | ·05 ·65 ·65 ·85 | 4·4 |
| 18 | 1, ·5 ·5 ·2 | 1.8 | ·85 ·85 ·1 | 4·0 |
| 19 | | 1.2 | 1, ·5 ·65 ·5 ·2 ·5 1·0 | 3·37 |
| 20 | ·5, 1, ·2 ·5 | 1.0 | ·5 ·5 | 3·2 |
| 21 | | 0.5 | ·65 ·05 ·5 1·0 ·5 | 2·64 |
| 22 | ·5 ·1 ·05 ·5 ·1 | 0.5 | ·5 | 2·6 |

**Figure 5: Shim Location and Adjustment Record**[3]

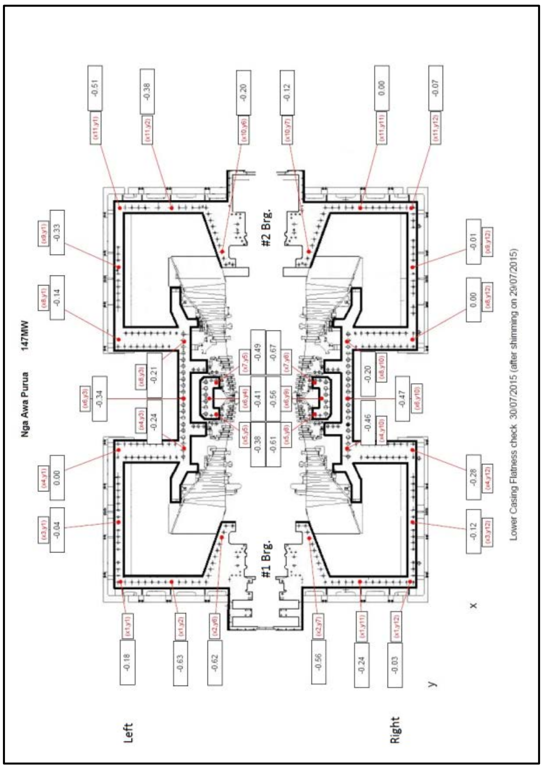



**Figure 6: As-Left Lower Casing Flatness**[3]

The results presented in Figure 6 are displayed as 'all negative'. The highest points have changed: from three of the corners previously; to two points near the middle of the sides, and one point near the right rear corner. It can be seen that there is less variation in the measurements; i.e. the turbine casing is flatter. Due to time pressure only one attempt at flattening the casing was made. Given at least one more shim alteration, it would have been possible to flatten the casing even further; potentially to within 0.3mm variance.

### 5.7 Shaft Alignment Adjustments Post Casing Shimming

The shaft alignment measurements carried out after the turbine casing had been shimmed were conducted using the Easy-Laser E710 measurement system.

Initial results showed that the coupling gap was open at the bottom by 0.22mm. This is consistent with records showing that the generator had been raised significantly at the rear; probably unwittingly accounting for the turbine casing subsiding at the front.

Since the turbine casing was by this time relatively level, it was planned to lower the rear of the generator by about 2.7mm to correct the alignment.

Adjustments were made to the generator in the vertical and horizontal directions, bringing the alignment back within tolerance.

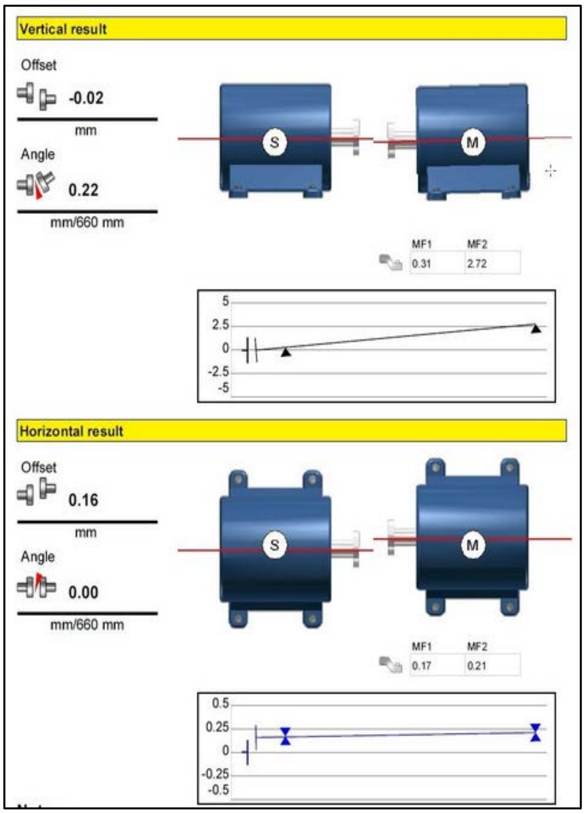



**Figure 7: Shaft Alignment after Casing Shimming**[3]

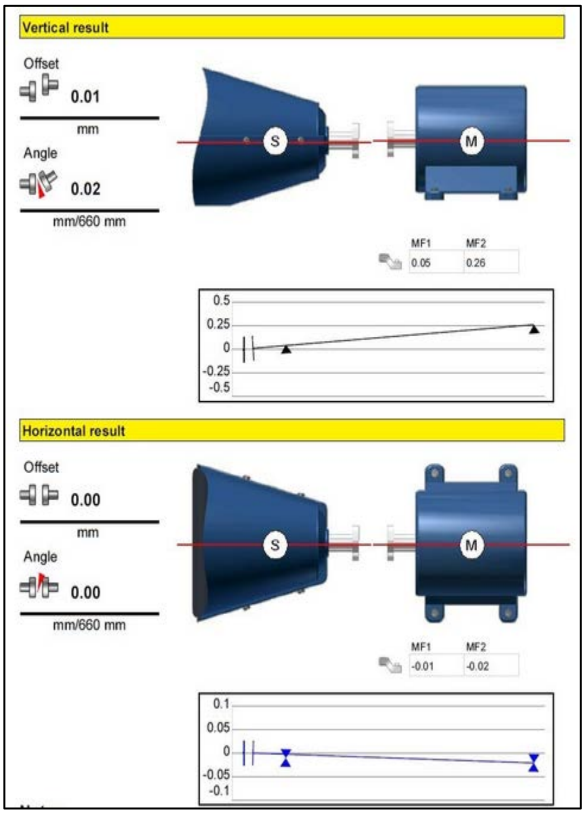



**Figure 8: As-Left Shaft Alignment**[3]

It is interesting to note that: based on the as-found alignment results, the rear of the generator could have been lifted by approximately 0.5mm to correct the shaft alignment as it was at that time. This action would have addressed only a symptom of the plinth movement that had been occurring. The final approach taken has been to address the issues at a slightly deeper level; where the root cause of the misalignment has been tracked back, and an effective and efficient solution implemented.

## 6. OWNER/OPERATORS ROLE

Operators must consider maintenance costs and the reliability of the plant with a long term view. If root causes are not addressed, symptoms of these issues may repeatedly appear and require corrective action at regular scheduled maintenance intervals. Some of these repairs may add significant cost and time to the outages such as: seal fin replacement due to rubbing damage, erosion damage due to increased clearances, and bolting replacement. In addition, there is an increased risk of unscheduled downtime due to deterioration in the condition of the machine. These costs far outweigh those involved with the planned measurement and correct realignment of all components of the machine train. Turning a blind eye to potential issues and rushing to return a machine to service is at best false economy, at worst very costly.

This highlights the need for plant operators to be technically involved during maintenance work on their machinery, to enable them to make the best decisions regarding the long term future of their multi-million dollar plant. There is a tendency for manufacturers of turbo machinery to hide the full picture from their customers, particularly during the warranty period. The years following the expiration of this period have resulted in some unexpected surprises for some plant owners. Owners of plant must ensure that during major outages they put in place experienced supervisory and technical resources that they can rely on to give objective and impartial expert advice.

## 7. CONCLUSION

TG set operators should be aware that correct alignment of the machine train is a keystone of reliable operation. It has been the experience of ProGen that machine train alignment problems due to plinth movement are a common occurrence around New Zealand and South East Asia. The measurement and diagnosis techniques outlined in this paper are a useful description of how these problems can and have been overcome, using expertise gained around New Zealand and the wider Pacific region. Modern laser measurement techniques form a valuable part of the outage 'toolbox'; allowing complex alignment issues to be quickly and easily interpreted, quantified, and rectified; rewarding the owner with reliable and efficient power generation.

**Figure 9: Measuring Casing Flatness**

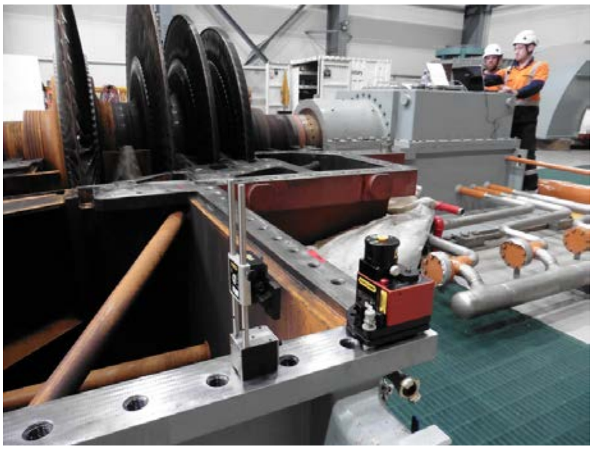


**Figure 10: Measuring Casing Flatness**

**Figure 11: Measuring Diaphragm Bore Alignment**

**Figure 12: Measuring Diaphragm Bore Alignment**

**Figure 13: Measuring Shaft Alignment**

**Figure 14: Measuring Embedded Plinth Datums**

## ACKNOWLEDGEMENTS

ProGen would like to acknowledge the support of the following people who assisted with technical discussions that supported the development of this report:

Chris Morris – Geothermal Engineer – Contact Energy, Wairakei, New Zealand.

Alan Robinson – Technical Director, ProGen, New Zealand

Andrew Nish – Geothermal Turbine Specialist – Mercury Energy, Rotorua, New Zealand

Roald Haarberg – Technical Specialist – Easy-Laser - Sweden

## REFERENCES

1. Morris C, Robinson A.: Geothermal Turbines – a Maintainers Perspective. *Proc. World Geothermal Congress* (2015)

2. Easy-Laser: Instruction Manual Revision 11.1 *https://easylaser.com/en-US/Lifecycle-Support/Manuals.aspx*

3 ProGen: Nga Awa Purua 147MW Turbine Overhaul Report (2015)