Gas Turbine Rotor Bow – Experimental Surface Measurement

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This report discusses the study undertaken to provide improvements to an experimental apparatus and procedure under continued development to accurately validate numerical studies regarding the thermal bow of a gas turbine compressor shaft. Validation through experimentation will support current research that attempts to understand the influence and significance thermal bow can have on the tendency of an engine to experience the Newkirk Effect. To obtain experimental rotor bow data the procedure and apparatus have undergone an iterative process towards that which allows for the accuracy of the data to be initially quantified. A clear understanding of the areas of uncertainty present in the data allowed for direct methods of improvement to be trialed and implemented. The experimental results of the current iteration have shown positive progress towards repeatability; however, continued improvement is required in the areas identified to validate the numerical predictions. The integrated flexibility introduced as a result of the developed experimental apparatus, procedure and postprocessing techniques have led to a significant increase in the available scope regarding the testing that can now be performed experimentally. The procedural mitigation mechanism of dry cranking is one such avenue of testing that has revealed validity in the experimental approach given the likely trends seen in the relatively small data pool that has been developed so far.

I. Introduction

A. Motivation and Aims

In recent years parametric research has been conducted regarding thermal rotor bow and the Newkirk Effect [2,4,5]. Numerical data has been obtained via computational methods and is being used to study the effect various parameters have on the onset time, duration and the severity of thermal rotor bow. While there have been attempts to reproduce experimental data as a form of validation of the numerical analysis, the technique and procedure have yet to deliver significantly accurate accounts of thermal rotor bow [1-4]. As gas turbine engines are used in a wide range of industries throughout the world it is increasingly important that this phenomenon be further understood. It is hoped that this study will contribute towards a solution to best mitigate the effects and potential consequences of thermal rotor bow [3, 5]. The following work was conducted to rectify the limitations identified in the previous studies cited while building on the recommendations made. Additionally, this work studied the uncertainties prevalent in such a method to better appreciate the accuracy of the experimental approach and the results obtained. Once it had been demonstrated that rotor bow could be observed experimentally, the results were to be used to study how particular procedural mechanisms, such as dry cranking, influence the behaviour and significance of thermal rotor bow.

B. Thermal Rotor Bow

After shutdown of a gas turbine engine thermal gradients form once the engine has ceased to rotate. A thermal gradient is developed within the gas path annulus and radially within the compressor assembly via the natural convection heat transfer that occurs inside the compressor. This thermal gradient causes differential thermal contraction as the top of the compressor rotor cools at a slower rate than the bottom. This causes the compressor and shaft assembly to warp and bend, referred to as thermal rotor bow [3, 6]. A gas turbine engine having developed rotor bow which is then restarted can experience significant surface contact and rubbing between the compressor stators and rotors; this is known as the Newkirk Effect [7, 8]. This unintended level of contact can result in damage to engine components and in extreme cases may cause engine failure [9].
II. Experimental Development – Phase I

The report has been structured to delineate between two distinct phases in the experimental development during this project. These are; the initial Phase, prior to observing rotor bow (i.e. Phase 1) and the later part of the work conducted where experimental rotor bow had been observed and further studied (i.e. Phase 2).

A. Experimental Apparatus and Instrumentation

Previous experimental work identified limitations in the design and the procedure of the experiment inhibiting accurate data gathering to validate numerical studies. The difficulty was developing a uniform surface temperature of the drum prior to testing [5]. As the previous experiment required the rotor to be moved from a kiln to the test stand, a thermal gradient had already been developed in the rotor and so invalidated the experiment’s attempt to record the effects of a thermal gradient developing purely by buoyancy [5].

At the onset of the work conducted in this study a new design of the apparatus and heating method had thought to eliminate the issue regarding non-uniformity of the surface conditions for the purposes of testing. Figures 1a and 1b depict the features of the Phase I design. In this design an aluminium frame supports the rotor drum which is fitted inside the steel case during heating. See Appendix A for the general drawing with dimensions of the rotor. The insulating material allows for the drum to reach temperatures in excess of 600 K. To heat the drum, three 2000 W heat guns deliver approximately 873 K (600 °C) airflow at a rate of 500 L/min. To accurately collect the data, two profile scanning lasers simultaneously track the surface deformation of the drum to a resolution of 15 micrometers. Phase I used a thermographic infrared (IR) camera to obtain the primary thermal data.

![a) Aluminium frame and equipment [10] b) Heat guns and insulating case]( Figure 1. Experimental apparatus and instrumentation used during Phase I)

B. Experimental Procedure

Developing the experimental procedure to that which is detailed in Appendix B was an iterative process. The procedure is such that if altered the repeatability of the results may be negatively influenced. While each step is important to gather accurate data, the experiment has three key phases (heating/transition/cooling) with some critical points that are required for the basic bow phenomenon to be captured. It is critical to heat the rotor evenly with the intention to develop a uniform thermal profile of the surface. Figure 2 shows an IR image of the rotor surface at the onset of the cooling phase. The transition phase sees the heating case removed and the rotor adjusted as required. It is critical to ensure the steps within the transition phase are carried out methodically and efficiently. This is to ensure that the laser and thermal data captured contains the salient information at the onset of the cooling phase (i.e. during the development of the thermal gradient), such that thermal rotor bow will be observed. For a detailed discussion of the procedure including the origins of the development please refer to Appendix B.

![Figure 2. Infrared image of the rotor after completion of the heating phase [11]](image)
III. Uncertainty Analysis

Developing a sound understanding of the variables affecting the results is imperative in understanding the uncertainty inherent with any experiment. Without a proper understanding of the possible errors in the data there is no real understanding of the reliability and the accuracy of the results [12]. Ideally the uncertainty analysis is conducted prior to the development of an experiment and the experiment is built around those findings; this in theory assists to circumvent the significance of the uncertainty in the results one intends to ascertain [13].

A. Thermal Plume Distorting Laser Signal

Density gradients within the thermal plume affect the refractive index of the laser light propagating through it. This causes discontinuities in the refractive and reflective angles seen by the laser beam creating noise in the signal [14]. The fluctuating air density associated with the buoyant plume results in uncertainty in the optical measurement from the laser profile scanners. Figure 3a depicts a three-minute test during which a heat gun was aimed and run through the laser beam between the rotor and the laser housing, replicating the effect of the buoyant plume in a controlled, exaggerated way. Timings are indicated by the red dotted lines. The first and last 30 seconds show the laser profile result with the heat gun off. For the times between 30-60 seconds and 2-2.5 minutes, the gun was run at medium power (250 L/min at 600K) and the 2-minute section between had the gun at full power (500 L/min at 600K).

![Figure 3a. Laser test results - Thermal plume](image1)

![Figure 3b. Laser test results - Fluorescent lights](image2)

The severity of the plume effect from the hot rotor is significantly less than that observed by directly measuring through the gun’s mass flow. However, this simple test confirms that the laser measurements are affected by the presence of density changes in the flow, and that the effect on the distance measurement is of the order of 400 µm or 0.08% of the absolute distance measurement (i.e. approximately 470 mm). This source of uncertainty was able to be quantified using the thermal data obtained during each experiment, as will be discussed further below.

B. Effect of Fluorescent Light on the Laser Signal

A test revealed that the fluorescent lights in the laboratory affected the distance measurement of the laser scanners. The results of this test are displayed above, at Figure 3b. Having the lights on was shown to create a constant discontinuity, decreasing the scanned distance measurement by approximately 1 mm or 0.2% of the absolute distance measured by the laser scanners. This source of uncertainty was mitigated procedurally whereby subsequent experiments were run without the presence of the fluorescent lighting in the lab.

C. Frame Distortion due to Thermal Growth

Having not been able to detect rotor bow in the results of several initial tests, the behaviour of the aluminium frame during heating and cooling was scrutinised. While the heating method was effective in achieving a rotor surface temperature in excess of 600K, it was difficult to prevent heat soak into the frame. The thermal growth and contraction of the frame resulted in unwanted movement of the entire rotor assembly. This effect translated into the laser scanner results; indicating an exaggerated contraction rate of the upper surface and a decreased contraction rate of the lower surface, effectively dampening the predicted bow phenomenon. A linear variable displacement transducer (LVDT) recorded the average vertical growth of the frame to be 420 ± 20 µm. The subsequent poor signal to noise ratio meant that the thermal distortion was the most significant source of uncertainty in Phase I. Efforts were made to mitigate the heat transfer causing thermal growth of the frame. Several methods of cooling were tested. Heat fins were used to increase the surface area of the frame to aid conduction and radiative cooling [15, 16]. Steel plates allowed hot air to be deflected away from the frame and modified
brackets were used to reduce the conduction path between the heating case and the frame. Figure 4a depicts the heat fins installed onto the frame while Figure 4b indicates the heat transfer through the fins. Figure 4c is an IR image towards the end of the heating phase, indicating the elevated temperatures of the aluminium frame. Accounting for the error in the measurement itself a reduction in the vertical growth of the frame of between 7-20% was gained from the use of these mitigating measures. Despite efforts, the uncertainty due to thermal growth of the frame was unable to be eliminated entirely using this approach.

Figure 4. Various images indicating the fins to prevent the heat transfer into the aluminium frame and subsequent heat transfer captured using IR devices.

IV. Initial Results – Phase I

Figure 5 allows for comparison of the experimental results with the numerical prediction of the aluminium rotor as it cools. The numerical prediction was developed using a conjugate heat transfer (CHT) computational fluid dynamics (CFD) simulation that was then coupled with a finite element method (FEM) [10]. As can be seen when comparing the curves, the aluminium rotor displays negligible rotor bow both numerically and experimentally. Rotor bow that is indicated in the experimental result (i.e. in the order of 2-3 μm) is within the stated 15 μm resolution limit of the lasers and is therefore negligible. This is highlighted by the numerical prediction as the upper and lower surface curves display very similar gradients, indicating they both cool at a similar rate. This is non-conducive to rotor bow. The blue lines in Figure 5 show the raw experimental data taken from the laser scanners. A kriging model was used to interpolate the raw laser data predicting the experimental mean of the signal within the noise, as well as develop an error prediction in the laser data as a function of rotor temperature[17-20]. Equation 1 indicates the general form of the function applied to each set of results, used to quantify the measurement uncertainty in the laser signal due to the thermal plume at any point during an experimental run. It was assumed that the standard deviation of the measurement error, Δδ, was proportional to the ratio of rotor surface temperature, \( T_r \), relative to the ambient temperature in the lab, \( T_a \) and the rotors maximum temperature, \( T_{max} \). A maximum likelihood estimate was used to predict the coefficient of proportionality, c.

\[
\Delta \delta = \pm c \left( \frac{T_r - T_a}{T_{max}} \right) (\mu m)
\]

The benefits of this particular surrogate model is its gaussian regression processing that allows for optimisation of the predictions when determining trends in a signal with a large noise disturbance [21].

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V. Experimental Development – Phase II

During the initial research using the above derived apparatus and procedure, several limitations were identified. A solution was required if rotor bow was to be shown experimentally. The following section indicates how these limitations were addressed to eliminate and or mitigate their consequences.

A. New Apparatus and Instrumentation

1. Cold steel frame

In light of the failed effort to adequately remove the heat from the aluminium frame, a secondary steel frame was designed and utilised during the cooling phase of the experiment. The steel frame, shown in Figure 6a, was not subject to the same heat soak to that of the aluminium frame, as it was kept away from heat sources until the completion of the heating phase. The cooling phase commenced once the rotor was positioned onto the steel frame where it was simply raised thanks to the added flexibility built into the existing aluminium frame. The rotor sat within specifically designed mounts, shown in Figure 6b. While some heat transfer between the hot rotor and the steel frame does occur, the intentionally large thermal mass of the steel frame has minimised this effect.

![Figure 6. a) Installed secondary steel frame (blue) [10] and b) a close up of the rotor mount](image)

2. Steel Rotor

Given the results indicated in Figure 5 further attention was drawn to the behaviour of the rotor material. A CHT CFD structural FEM prediction of the steel and aluminium rotors, conducted by my supervisor SQNLDR (Dr) E. Smith, identified a significant difference in thermal bow response between rotors, despite near identical geometries. The difference in the maximum thermal bow between the two rotors can easily be seen in Figure 7. Having a thermal conductivity approximately 15 times higher than steel [15], the peak thermal gradient of the aluminium rotor was found to be 1 K, compared to approximately 38 K for the steel rotor. The relatively large thermal conductivity of aluminium was preventing the development of any significant thermal gradient that is required to cause differential cooling conducive to thermal bow. In this instance a 1 K thermal gradient is negligible as it results in a 12 \( \mu \)m bow, once again below the 15 \( \mu \)m resolution limit of the lasers.

![Figure 7. FEM image of distorted rotors [10]](image)

3. Instrumentation and Integration

Phase I consisted of the two laser scanners each recording to a separate computer. This led to issues in experimental runs where the lasers could not maintain a consistent frequency. Synchronisation of the lasers was achieved via an ethernet switch, allowing the lasers to operate from a single computer. This considerably simplified the experimental procedure as well as reduced time required to manipulate the laser data while post processing.

As described above a single IR camera was used to capture the thermal data during the experiment. Having a single point of reference degraded the thermal analysis during the experiment. Limitations of the IR cameras range required recording of the data to be stopped and restarted during the experimental runs, adding complexity to the
procedure. To combat the afore-mentioned limitations, Phase II utilised eight pyrometers as well as two IR cameras, resulting in a significant increase to the thermal fidelity of data gathered for each experimental run. Figure 8a depicts the current apparatus with the addition of the mounted instrumentation installed during Phase II. Six pyrometers, three focused on the top surface and three on the bottom, provided axial thermal data while two additional pyrometers gained accurate thermal data during the heating and cooling phases. Figure 8b depicts the mounts used to install the top and bottom pyrometers. Visual scales aided the correct alignment of the equipment. While one IR camera was used to monitor the rotor as before, the additional IR camera allowed for larger scale images to be captured throughout, as seen in Figure 4c.

VI. Steel Rotor Results – Phase II

Integrating the modifications and methods mentioned above, thermal rotor bow was observed experimentally. Figure 9a depicts the surface deflection data at the defined top dead centre (TDC) and the bottom dead centre (BDC) positions. It indicates the top surface cooling at a slower rate than the bottom due to the induced thermal gradient. Figure 9b shows the difference between these curves, revealing the thermal rotor bow measurement along with the numerical prediction for the steel rotor. Similar to previous results, a kriging model predicted the mean and uncertainty curves also indicated.

The peak bow predicted numerically was approximately 260 µm at five minutes, while experimentally it is seen to be about 90 ± 20 µm at nine minutes. This discrepancy is significant and therefore required further understanding of possible causes behind the misalignment between the two results. While previous experimental results have shown fewer discrepancies with the numerical predictions, the current iteration of the experiment is showing encouraging progress in that repeatability of the results has to some extent occurred. Despite the initial inconsistencies from the numerical prediction this result is considered a successful experimental outcome. The variation between the results as well as the unexpected initial negative bow response will be discussed below.
Figure 10 displays the results of two individual experimental runs. While the uncertainties that have been discussed above remain within each result, similarities and trends can be drawn between the two. The Newkirk Critical Bow (NCB) line is an assumed threshold bow limit above which an engine would experience the Newkirk rubbing effect.[11] In this case it is an arbitrarily selected value used to compare the severity (peak bow), the onset time (time to reach the NCB threshold) and the duration (the time above the NCB limit) of different sets of results. For context, these metrics are highlighted in the typical thermal rotor bow profile shown in Figure 11. The two individual results in Figure 10 show agreement between each respective metric within 5-30%. Again, whilst this is considered a large discrepancy, it is a promising sign towards repeatability in the results of a newly developed experimental apparatus and procedure that until recently was yet to capture rotor bow.

![Figure 10. Bow results of two individual tests](image1)

![Figure 11. A typical thermal rotor bow profile [11]](image2)

**VII. Analysis of a Procedural Mechanism**

Given the added flexibility built into the experiment during Phase II and the increased likelihood of repeatable results, the experiment was used to study the effects of dry cranking. This is a procedural mechanism used many operators to mitigate thermal rotor bow whereby the starter motor would turn the engine forcing cool air through it to cool the engine symmetrically [9, 22, 23]. The cooling occurs to a point where the temperatures within the engine would not lead to a thermal gradient causing bow greater than that of the NCB limit. The opportunity to test how procedural mechanisms influence the magnitudes and trends of the various metrics experimentally has significant advantages over a numerical simulation. While a simulation may take several days or weeks, the experiment can be completed in a matter of hours and provides real world results without the assumptions used in numerical work.

Figure 12 shows the results of several experiments testing cranking effectiveness. Given the uncertainty in the experiment the image created by the raw data seems somewhat convoluted. From the data however, specific information could be drawn to observe how the previously mentioned metrics were influenced by crank time.

![Figure 12. Four individual results testing the effectiveness of dry cranking against a baseline result](image3)
Figures 13a-f display the results of two individual sets of dry cranking trials. During these trials 30 seconds, one, two, and five minutes of cranking were tested. The figures on the left reflect the results of a single cranking trial, while those on the right compare the two trials displaying averaged metric values to indicate the trends in the data. Given the currently small data sample a few anomalous points are observed. However, severity, onset time and duration all show a general and anticipated trend in that they all decrease with increased crank time. Cranking the rotor causes it to cool evenly, resulting in a diminished thermal gradient from which rotor bow would develop [22].

Figure 13. Results of two individual dry cranking trials
The large error bars, specifically those for onset and duration time, highlight the significant uncertainty still present in this iteration of the experiment. Future work will see these errors reduced, while more data to analyse will allow for development of the already promising trends seen in these initial dry cranking trials.

VIII. Experimental Limitations and Uncertainty – Phase II

The experiment has matured throughout this project, such that rotor bow can now be observed with a degree of repeatability. With the increased flexibility and fidelity in the data, the results obtained allow extended analysis and parametric studies to be performed. There are however limitations still present due to the uncertainty within the current working experimental apparatus and procedure. While some limitations have previously been highlighted this section will discuss the irregularities in the observed experimental data preventing a clear validation between these results and the numerical predictions. Figure 9b highlighted a misalignment between the experimental results and the numerical predictions. The significant difference was in the severity of the bow and the time at which the peak occurs. It was also indicated that there is an initial negative bow observed. It is not yet known if these two inconsistencies with that of predicted numerical results are linked, however it is believed that if it can be determined why the bow plot indicated irregular negative behaviour, and this is rectified, the results are likely to converge.

Some preliminary studies to explain the observed negative bow were conducted. While there may be several factors causing the irregular behaviour one explanation could be an unexpected thermal gradient at the onset of the cooling phase. A benefit of the additional thermal data obtained from the pyrometers was that this theory was able to be tested. Figure 14 indicates that it was found that rather than beginning at zero, or slightly above zero, as expected (due the time required to remove the heat box), the temperature difference between the top and bottom rotor surfaces was negative (i.e. the bottom surface was hotter than the top).

It was initially thought that there was a procedural oversight causing the temperature difference (i.e. the rotational position of the rotor at the completion of the heating phase) however testing proved this not to be the case. A second theory was investigated.

It was inferred that the eccentricity of the rotor (i.e. the rotor’s imperfect shape leading to out of roundness) may have led to a section of the rotor heating more so than the remaining surface and that this was obscuring the results. A further test where the original TDC datum position was rotated relative to its original position initially revealed that this assumption may have been correct. The results of this test are shown in Figure 15, indicating a positive thermal gradient, as predicted. As a result, the new orientation of the drum and its datums were adopted and several tests were re-run.

Postprocessing the new data revealed the irregular surface temperature disparity between the top and bottom surfaces had re-emerged. This prompted a closer analysis of the thermal profile of a standard experimental run compared to that which was subject to a dry cranking segment prior to the cooling phase. This was undertaken in order to understand why this difference in the data was occurring. Figures 16a and 16b highlight the difference in the thermal profile between a standard run and the irregular behaviour observed for the dry cranking case during the initial stages of the cooling phase. Note that Figure 16b displays the results after five minutes of cranking has occurred. In the instance where cranking has occurred, the thermal gradient initially behaves opposite to that which is expected, with the top surface cooler than the bottom. At approximately two minutes the thermal gradient
returns to as expected, with the top at a higher temperature than the bottom. It is yet to be understood why this phenomenon is occurring or its significance on the remaining data for each experimental scenario. To fully appreciate the irregular behaviour, with the intention to understand and reduce the significant discrepancies between the experimental and numerical results, it is essential that any further work include analysis of the thermal behaviour of the rotor during all phases of the experiment.

One of the largest sources of uncertainty in previous iterations of the experiment has been the non-uniformity of the initial thermal profile of the rotor. As seen in Figure 2 above, the current heating technique of the experiment (both Phase I and II) had significantly reduced any non-uniformity present in the thermal profile of the rotor. However, to what degree this was the case was unknown given the lack of temperature measuring equipment prior to Phase II. As can be seen in Figure 17 the pyrometers have revealed there is a good relation between the top and bottom surface temperatures in the centre of the rotor (where the laser scanners are focused). Though it also indicates an initial non-uniformity in the thermal profile axially across the rotor. This is seen by the difference between the top and bottom surface temperatures on the left and right hand sides of the rotor. While it is a positive result to somewhat eliminate the potential source of uncertainty at the centre of the rotor, further investigation is required to understand the effects that this discrepancy has on the results.

**IX. Conclusions**

The aim of this project was to address the limitations that previous experimental iterations had identified, further developing the apparatus and procedure to experimentally observe rotor bow. With the goal to validate previous and current numerical predictions and studies, thermal rotor bow was demonstrated experimentally however the task to show unequivocal validation of the numerical predictions remains.

Several sources of uncertainty have been identified, mitigated and or quantified where possible during the conduct of this work. While the experimental results developed thus far are promising, with the current iteration adding flexibility and showing signs of repeatability in the data, there is still significant uncertainty and noise inherent in the results leading to subsequent misalignments between the experiment and numerical simulations.

The results highlight the challenges associated with experimentally measuring thermal rotor bow. This is particularly evident where magnitudes are of the order of 200 \( \mu \text{m} \) and the environment through which measurements are taken is undesirable. This leads to unwanted and hard-to-predict thermal behaviour within the data and the surrounding experimental apparatus, resulting in low signal-to-noise ratios. The continued stray
nature of the experimental results from that of the numerical predictions indicates that more study is required to improve the understanding and quantification of the uncertainty still present, as well as the irregularities indicated by the thermal behaviour of the rotor during varied experimental runs.

X. Recommendations

There are many limitations that have been identified, which, if addressed, would significantly improve the experimental apparatus and procedure and subsequently lead to an improved overall result in the data that is obtained. However it is prudent to highlight several key points in this regard. Firstly, the initial quantification of the uncertainty in the laser data as a result of the thermal plume is a predicted value. Given the significance of the noise in this data it is important to further develop the understanding of the circumstances surrounding the laser measurement in this environment. To significantly improve the ability to gather, track and manipulate the laser data, the experimental setup would significantly benefit from additional point lasers in place of the surface profile scanners.

In addition, while the pyrometers have added valuable contributions regarding the thermal data now available, they have also allowed for the discovery of irregular thermal behaviour within the observed results. Further work should therefore also focus on understanding the thermal results now possible and in doing so gain a deeper understanding of the uncertainty associated with these recent additions to the apparatus.

Finally, without specific thermal and displacement data regarding the secondary steel frame, its behaviour is yet to be fully investigated. A detailed thermal analysis would significantly improve this understanding. With each of these areas further developed not only will the quality and the accuracy of the results improve, but the results would likely converge towards an improved validation of the numerical predictions.

Despite these revelations, this work is considered to have been a success given the trending repeatability in the results and the development of the experimental process used to demonstrate thermal rotor bow.

XI. Acknowledgements

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References


