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TEST RIG DEVELOPMENT FOR TURBOMACHINERY COMPONENTS

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ABSTRACT

New engine trends of higher exhaust temperature driven by retarded fuel timing to reduce NOX emissions and by increased power requirements, will likely cause turbomachinery housings and components to see heavier thermal transient loads and, as a results, greater likelihood of Failures. New capable qualification methods are required to provide successful design validation.

In this paper a new process to develop a qualification rig test, which account for various engine duty cycles, is outlined. Qualification test development involved the development of a successful accelerated endurance rig test that replicates field failures. It was necessary to conduct measurements on a running engine to identify duty cycle events with the most damaging potential. These measurements were utilized to design simplified test conditions that signify the influence of the critical parameters contributing to the failures.

The process was very successful in replicating field failures and developing superior designs with significant life improvements for turbine housings. The process can similarly be applied to most other turbomachinery components. An accelerated dual turbo gas stand endurance test and test procedure was thus developed and the test cycle time was shortened.

INTRODUCTION

The future field duty cycle challenges would necessitate the development of sophisticated qualification tests, which sufficiently represent field duty cycle requirements. Engine rating increases and emission trends of retarding fuel timing cause the turbine housing and other components to see severe thermal loads and high engine exhaust temperatures. Future duty cycle challenges will result in more failures. This situation calls for re-visiting current qualification tests to enhance the qualification test procedure to address these requirements.

The focus in this paper was on turbine housings, however, the approach and process is applicable to most turomachinery components. The development of a new rig test that can replicate potential failures in the field is needed to truly qualify the turbine housings for high temperature applications.

One purpose of this paper is to demonstrate the test procedure for turbocharger turbine housing thermal cycle qualification based on customer's duty cycle and reliability requirements. Various tasks towards that goal were started and involved experimental measurements and qualification endurance testing development. These efforts resulted in the development of accelerated endurance testing capable of replicating field failure of such demanding duty cycles. New housing design enhancements were successfully demonstrated on the developed qualification test.

FAILURE MODES

Turbine housings are available in both undivided (open) and divided inlet configurations. The undivided housing has a 360-degree flow path directed at the turbine wheel. The divided housing has a divider that separates the housing bilaterally into two side-by-side passages. During aggressive operation conditions failure modes could be one or more of the following:

- The housing may distort causing a turbine wheel rub.
- The housing outer wall may crack which would result in an exhaust gas leak.
- The tongue or divider wall may crack and break off, resulting in turbine wheel damage.
- The divider wall may distort causing a flow imbalance between passages and degrade performance.
- The turbine housing inlet flange may crack or distort which would result in an exhaust gas leak.
- The turbine housing discharge flange may crack or distort which would result in an exhaust gas leak.

Figure 1 shows an example of a turbine housing external cracking at the volute of a dual entry housing under aggressive field duty cycle conditions. The crack initiated close to the volute-to-flange connection and propagated circumfrentially in the flow direction. Figure 2 shows an example of a turbine housing cracking at the flow inlet flange for a divided inlet configuration during aggressive field duty cycle. The crack initiated on the inner surface on the volute entrance and propagated externally to the outer flange surface.

Figure 1: External Volute Crack of A Dual Entry Housing.

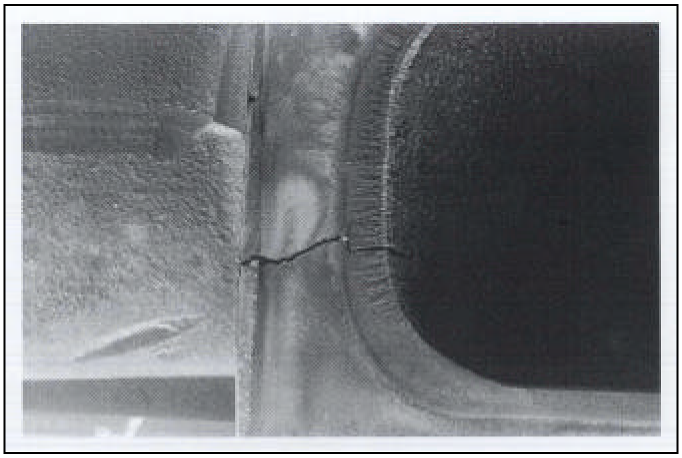

Figure 2: Inlet Flange Crack for Divided Wall Housing

QUALIFICATION OBJECTIVES

The objectives of this qualification procedure are to qualify turbine housing and heat shroud per customer's duty cycle and reliability target requirements.

Typically, the requirements in the product specification ensure that the turbine housing and heat shroud design are adequate for various service conditions. The product specification requires a thermal cycle test for a turbine housing which is expected to simulate potential field cracking and/or warpage of turbine housings. The requirement could be one or more of the following:

I. To qualify a turbine housing by passing a simulated Engine Endurance Test or

II. To qualify a turbine housing design for a specific operating duty cycle.

The requirements in a product specification should ensure that the turbine housing and heat shroud design is capable of meeting reliability requirements specified by the customer. The reliability requirements are specified in terms of reliability target in the field (R) at specified confidence level (CL) for a given mission or duty cycle. This will require that a specified number of units to be tested for specified number of hours and subjected to appropriate representative thermal cycling. The number of units to be tested and the number of hours can depend on the reliability requirements, the specified confidence level and the duty cycle mission.

APPROACH FOR QUALIFICATION TEST DEVELOPMENT

The efforts involved transient temperature measurements and thermal imaging (Reference 1) on the turbine housing and the center-housing flange during thermal transient and steady state condition. In addition high temperature strain measurements at critical locations of the turbine housing where external cracking are typically observed was conducted. A special technique to compensate for the thermal drifts was utilized.

Qualification test development involved the development of a successful endurance rig test capable of replicating potential field failures. It was necessary to conduct measurements on an engine undergoing such severe duty cycle conditions. These measurement would then be utilized to design simplified test conditions that signify the influence of the critical parameters contributing to the failures. Replicating the engine thermal cycling duty cycle on the gas stand was of great interest to accurately capture field conditions on the gas stand and to qualify new design enhancements. Accelerating the cycle was accomplished by dialing-in accelerating parameters with known effect on the housing stresses, and accordingly, with regards to low cycle thermal fatigue.

An instrumented housing and an instrumented center-housing flange were utilized on the gas stand to provide correlation between gas stand test environment and actual engine endurance test. The studies provided an understanding of the thermal cycling conditions of the engine and provided some explanation as to why the test would replicate actual field duty cycle. The advantage of the development of an accelerated thermal cycling rig is to eliminate the need for the expensive engine endurance testing. Also, a dual gas stand rig would provide the capability to test more than one sample simultaneously and comparing a new housing design to a baseline design under the same testing condition and environment. This effort resulted in the development of an accelerated test rig and the establishment of a new test procedure for turbine housing endurance testing which is capable of simulating aggressive duty cycle requirements. Hardware with the new design enhancements was developed and prepared for endurance testing (Reference 2). The endurance test was compared to a baseline design in a split type of a test on the new developed accelerated rig.

In summary, the program objectives were: I) To develop a successful accelerated endurance rig test that can replicate severe duty cycle failures and that can be used for turbine housing qualification testing and II) To outline a process for developing such accelerated qualification tests which replicates failure modes and correlates to field duty cycle.

ENGINE DUTY CYCLE

Thermal transient measurement cycles were conducted on a running engine with a severe duty cycle. The results provided realistic boundary conditions and thermal distribution fields for the modeling efforts (Reference 3). Additionally, these results were utilized for calibrating and validating the analytical model, which was utilized to understand effect of accelerating factors (Reference 4). The accelerated engine thermal cycle test is shown in Figure 3. Figure 3 shows Engine torque and speed during the thermal cycle. The turbine inlet temperatures, turbine outlet temperatures and exhaust manifold skin temperatures are also shown in Figure 3 for both the acceleration and de-acceleration portions of the cycle.

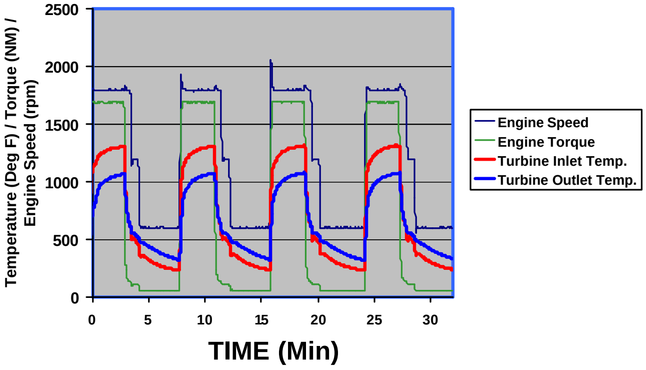

Figure 3: Accelerated Engine Thermal Cycle Test

The experimental efforts involved temperature measurements and thermal imaging (Reference 1) on the turbine housing and the surrounding back plate during transient cycles on engine cycle test as well as steady state condition such as rated, torque peak, high idle and low idle conditions. In addition high temperature strain measurements at critical locations of the turbine housing where external cracking were observed is conducted. A special technique to compensate for thermal drifts was developed.

Figure 4 shows a sample of the thermal imaging analysis, which carried on a running Engine. The picture illustrates the differences between the rate of rise and decay of temperature observed on the twin turbo passages due to wastegate location as well as inherent difference in the engine between various cylinders. That temperature variation was evident in the video captured during the engine cycle. Thermal imaging has provided a solid fundamental understanding and mental image for the behavior of the turbine housing thermal system.

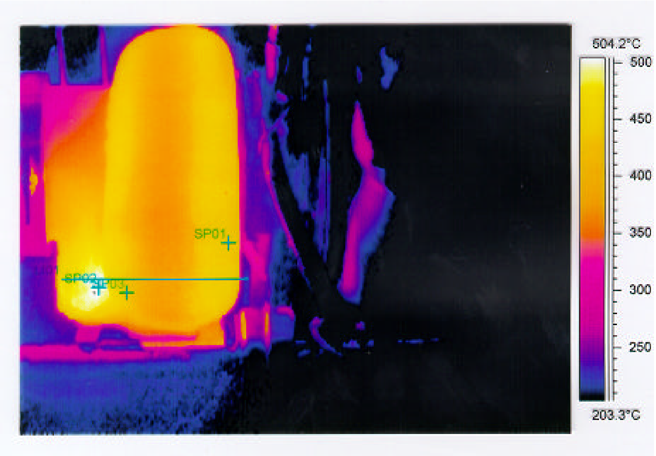

Figure 4: Thermal Image of Turbine Housing Showing Temperature Differences between the Two Ducts of the Twin Inlet Wastegated Turbine Housing

Figure 5 shows several critical regions on housing where skin temperatures and high temperature strains were measured during test rig development and compared to measurements on engine to ensure proper simulation of the cycle on the rig. These regions are typically: 1) the turbine flange at the middle span of the long side, 2) the volute scroll at the T-T section in close proximity to the V-band or bolted joint (at several locations in the radial direction) and 3) the center housing V-band flange or bolted flange. These regions could be different depending on housing design.

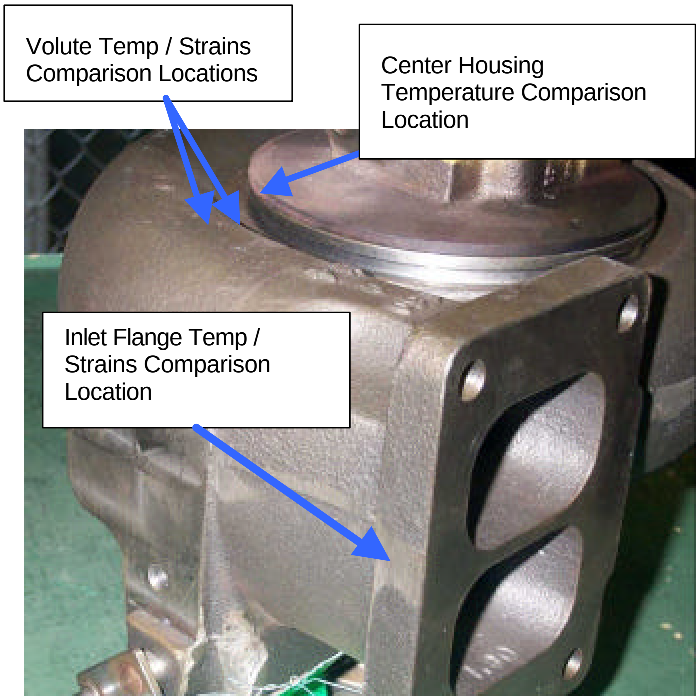

Figure 6: Locations on Housings for Temperature Comparisons of Analytical and Experimental Results.

THERMAL CYCLE DEVELOPMENT FROM FIELD DUTY CYCLE

It was necessary to examine customer's field duty cycle on engine and relating it to testing cycle in the lab. Events in the field cycle data with the most damaging potential were identified and translated into representative simplified thermal cycle (Reference 5). A low-cycle thermal fatigue program is utilized for that purpose.

Customer's field duty cycle parameters were measured. The data include measurements for:

- Turbine Inlet Flow Temperatures (Degree F/Degree C)
- Turbine Inlet Flow (Lb/Min / Kg/Min)
- Turbocharger Speed (rpm)
- Compressor Outlet Pressure (in-hg / mm-hg)
- Oil Supply Temperatures (Degree F / degree C)
- Oil Supply Pressures (bar)

Events in the cycle with the most damaging potential were identified. The field cycle is simplified and accelerated utilizing the developed analytical model.

Figure 6 shows an example of the simplified cycle where "T" represents the total cycle period. The figure shows both the heating up and cooling-down portions of the thermal cycle. Time period"T1 " represent the inlet temperature ramp-up period. Time period "T2" represents the period to reach hot steady state conditions. Time period "T3" represents cool-down period of the inlet temperature. Finally, time period "T4" represents the period to reach cool steady state conditions. The information for turbine inlet temperatures and flow, Oil supply temperature and pressure, compressor outlet pressure and turbo speed were extracted for various portions of cycle. The information was utilized to design a controlled cyclic operating condition for the gas stand (Reference 6).

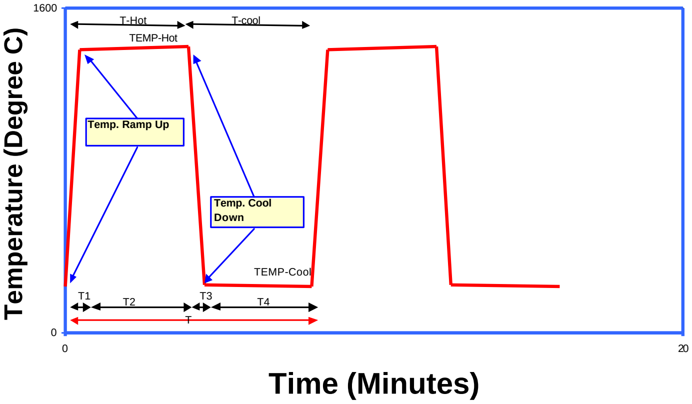

Figure 7: Simplified Thermal Cycle on Gas Stand.

GAS STAND THERMAL QUALIFICATION TEST DEVELOPMENT

A dual turbo gas stand rig is constructed in order to be able to simultaneously test a baseline design vs. a new developed design in a split type of test. Additionally the test can be used for differentiation between alternative designs. The housings are set up together with a diverter valve alternating the turbine inlet gas from one unit to the other as shown in Figure 7. The turbocharger is subjected to thermal cycling as measured on the engine endurance test cycle. Turbocharger oil temperature and pressure should be adjusted at the required specification. Turbine inlet flow should be set to match the engine specifications for both the temperature ramp-up and the temperature cool-down parts of the thermal cycle. Turbine inlet maximum and minimum temperatures should be set to match the engine specifications within 10 degree F. The total thermal cycle period is set at 8 minutes per cycle similar to accelerated engine test. The acceleration and decelerations portions of the thermal cycle are equal and set at 4 minutes each which is sufficient to ensure that the thermal profile has approached steady state conditions. This would result in shortening the total time required to conduct the test. Figure 8 shows a photo for the developed test rig.

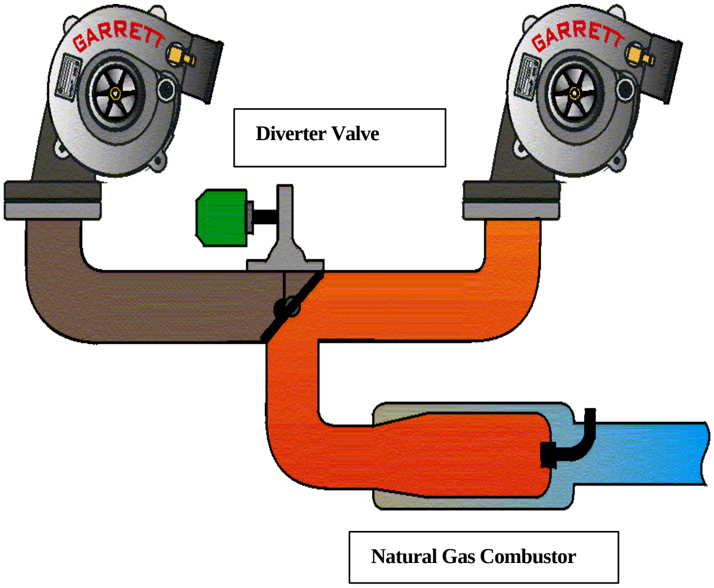

Figure 7: Schematic for Dual Turbo with Diverter Valve Gas Stand Test

Figure 8: Developed Thermal Test Rig.

INSTRUMENTATION

The gas stand should be equipped with appropriate instrumentation with the adequate sensitivity and control to dial-in the cycle parameters. All test parameters should be duplicated as dosely as possible for all units to aid in the comparison of results. Listed below are the typical parameters with their required accuracy.

Speed -Turbocharger Speed: +/- 200 rpm

Temperature -Turbine Inlet Temperature: +/- 4° .F , +/-2° C

Turbocharger Oil Supply Temperature: +/- 2° F, +/-1° C

Pressure –Compressor Outlet Pressure: +/-.01 Inch-Hg,
+ /-.25 mm-Hg
Turbocharger Oil Supply Pressure +/- 1.0 Psig,
+/- 0.1 bar
Air Flow- Turbine Inlet Flow ……… +/-0.1 Lb/Min,
+/-.045 kg/Min
Thermal Cycle - Period +/- 0.1 Minutes

TEST PROCEDURE

The turbine inlet flow at full Load Conditions [dM/dt] and at Low Idle Conditions [dm/dt] should be set as measured on the engine duty cycle. Turbocharger oil supply temperature and pressure, turbine inlet temperature and compressor Outlet Pressure should be set as measured on the customer application.
Turbine wastegate should opens and closes during at the right schedule during the test, using an external pressure source if needed.

Turbine inlet flow should be set to match the specification for the ramp-up and the cool-down portions of the thermal cycle. Compressor outlet pressure should be regulated at the specified level. Turbine inlet maximum and minimum temperatures should be set to match the above specifications within 10 degrees F. Rate of ramp-up rate of cool-down of the thermal profile can be fine-tuned by controlling the diverter valve speed. Thermal cycle period is usually set between 8 – 12 minutes to ensure that the thermal profile can approach steady state conditions for both ramp-up and cool-down of the thermal cycle. During the thermal cycling testing it is important to ensure that the gas stand does not run the compressor into surge or choke. The housing should be inspected every 50-100 hours to inspect for any sign of distress (leaks, cracks, rub, etc.).

The numbers of samples and test duration are determined based on customers reliability target (R) and confidence level requirements. The housing and shroud are checked for cracks, warpage, leaks, and wheel rubs. Also turbochargers require a performance test to be performed on the turbine wheel/housing combination before and after thermal cycling. Turbine Housing design is certified if it passes the required qualification tests. If the design does not pass the qualification tests, the design and material should be checked to insure that it meets product specifications. If it is determined that the materials and design were according to specification the turbine housing design and or material should be modified and re-qualified.

MEASUREMENTS ON THERMAL ENDURANCE RIG

Temperature measurements were conducted on the gas stand per the developed cycle to simulate the accelerated engine thermal cycle and correlated to engine measurements.

Figures 9-11 show skin temperatures traces vs. time on the thermal test rig as compared to measurements on the engine at various characteristic locations.

Figure 9 shows the correlation between gas stand and engine temperature measurements on the volute close to the V-band. Figure 10 shows the skin temperature correlation at the turbine housing center-housing flange (center housing side) as compared to measurements on the engine. Figure 11 shows the correlation on the flange at the middle span. These Figures show very good correlation at theses three characteristic regions of the turbine housing. Such correlation indicates that the rig as set was capable of matching the thermal cycles of the engine.

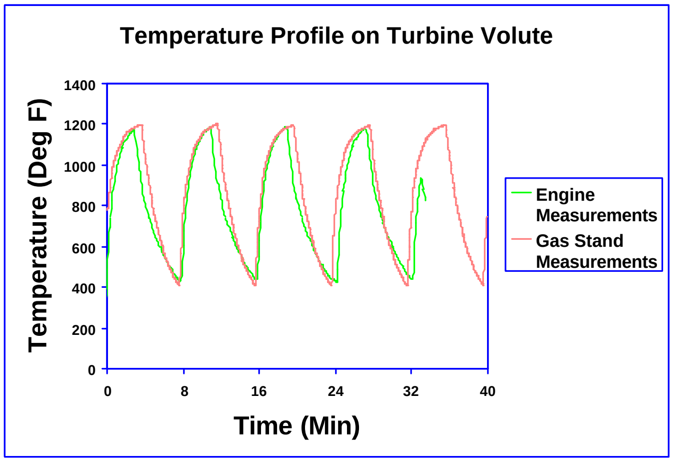

Figure 9: Comparison Between Gas Stand and Engine Temperature Measuerments on the Volute.

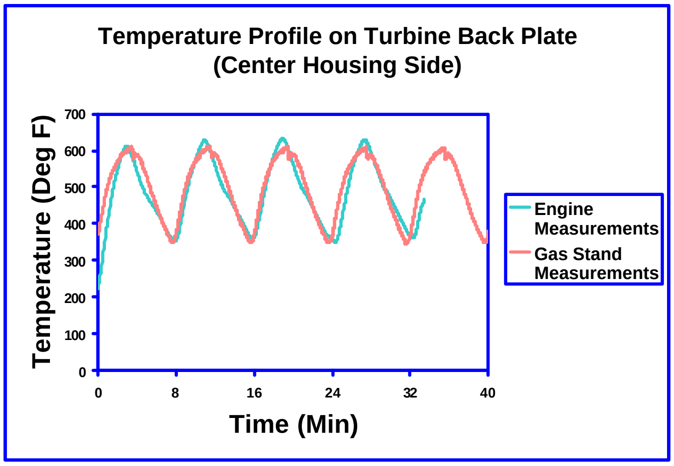

Figure 10: Comparison Between Gas Stand and Engine Temperature Measuerments on the Back Plate.

Furthermore, high temperature strain measurements traces vs. time were measured on the rig and compared to the engine measurements. Figures 12-14 show the comparison between engine strain measurement and gas stand at various locations on the volute close to the V-band

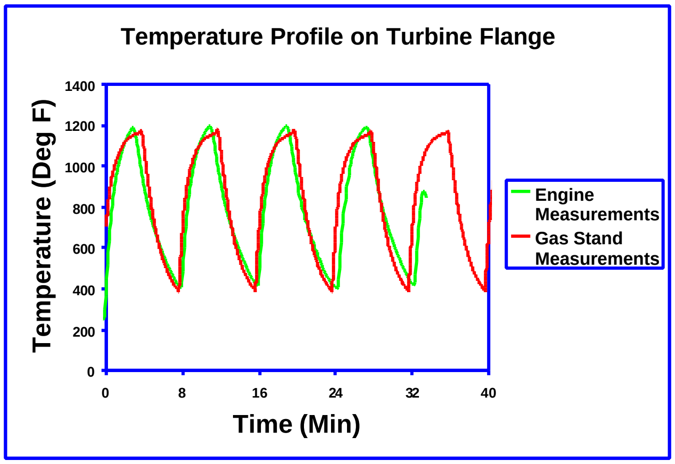

Figure 11: Comparison between Gas Stand and Engine Temperature Measurements on the Inlet Flange.

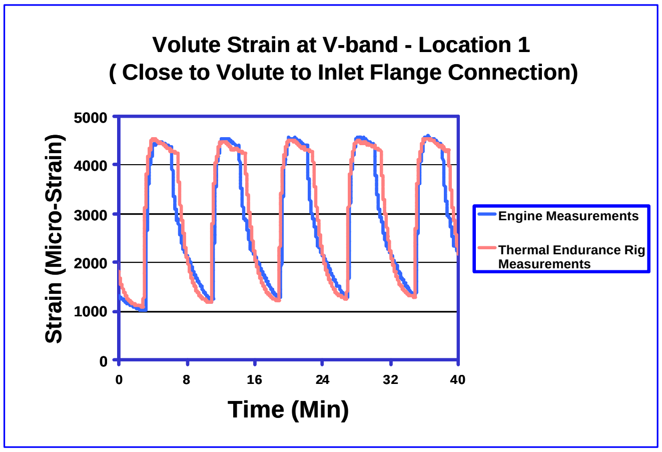

Figure 12:Comparison Between Gas Stand and Engine High Temperature Strain Measuerments at Location 1.

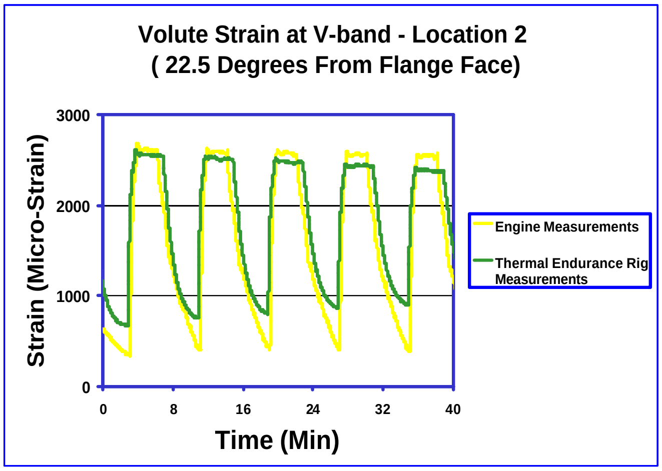

Figure 13:Comparison Between Gas Stand and Engine High Temperature Strain Measuerments at Location 2.

Figure 12 shows the correlation between engine high temperature strain measurements and the gas stand at the location close to the volute-to-flange connection. This represents the location of the highest strain measured and correlates to the location for V-band crack initiation as observed on the field engine testing with aggressive duty cycle. The correlation is very good. Similarly Figure 13 and 14 show the comparison at other locations close to V-band at 22.5 and 45 degrees to the flange face.

All the previous correlation indicate that the developed test rig will be able to produce similar failure modes as expected on the engine thus capable of replicating field failure for potential future aggressive cycles as explained further in the following section.

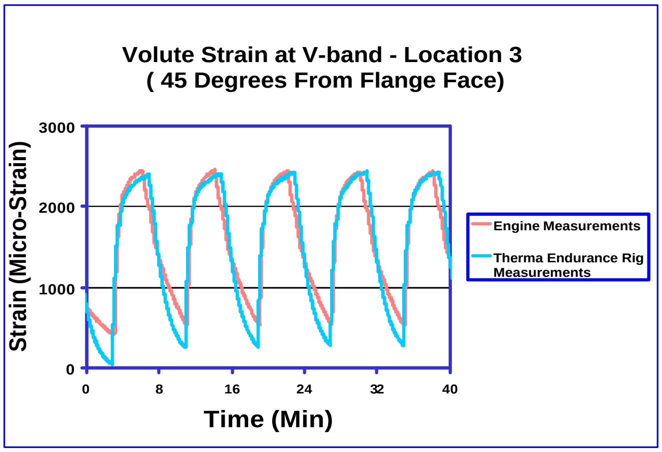

Figure 14:Comparison Between Gas Stand and Engine High Temperature Strain Measuerments at

FIELD FAILURE DUPLICATION

A successful endurance rig test should be able to replicate field duty cycles to qualify turbine-housing designs before releasing them to the service. The rig was utilized to test housings that experienced failures during aggressive duty cycle in the field. The rig was successful to replicate the housing cracking in a relatively short period of time. The housings have developed external cracking initiation at both the volute and at the inlet flange when examining housings after 50 hours of testing. Testing continued and the turbine housings were examined every 50 hours. After about 200 hours from initial testing the cracks have totally propagated thus resulting in leakage and complete failure of the housing. The failures replicate the failure mode in the field.

Figure 15 shows an example of the housing cracking at the volute near volute-to-flange connection. The crack propagated in the circumferential direction close to the V-band. Figure 16 show cracking on the inlet flange of the turbine housing. The crack propagated through the flange thickness. The failure on the gas stand occurred in about 200 hours (about 1500 cycles @ 8 minutes / cycle) of endurance testing with crack initiated as early as 50 hours (about 375 cycles @ 8 minutes /cycle). The cracks are similar to field cracks as seen in Figures 1 and 2. Based on these results, we have successfully developed an accelerated test that duplicates the field failure of turbine housing undergoing future aggressive duty cycles at the V-band and the inlet flange.

Figure 15: Baseline Turbine Housing Cracking at Volute after 200 Hours of Gas Stand Endurance Testing.

CONCLUSION

Thermal cycling qualification test should be based on field duty cycle requirements. Turbine inlet flow characteristics at both the ramp-up and cool-down portions of the cycle should be accounted for in the test procedure. A testing methodology that accelerates the critical factors of an operating environment responsible for the root-cause of a potential failure is necessary. Such accelerated rig and test development processes are imperative for successfully resolving problems and developing superior design and solutions in the turbomachinery field.

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