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NEW TURBOMACHINERY HOUSING DEVELOPMENT

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ABSTRACT

The purpose of this paper is to present a successful new design of turbine housing subjected to various duty cycles in the field. New engine trends of higher exhaust temperature driven by retarded fuel timing (to reduce NOX emissions) and by increased power requirements will likely cause turbine housings to see heavier thermal transient loads. The higher thermal loads will potentially increase the likelihood of thermal cracking. Accordingly, new innovative housing design methods and tools are needed to guide the design process and to prevent thermal-mechanical cracking. Qualification procedures are also needed to provide successful design validation.

Both analytical and experimental techniques are adopted in this work. Results of the analytical model were correlated to the experimental measurements for model verification. Analytical transient FEA analysis was utilized to understand the effect of thermal loading on the turbine housing. The model was calibrated against engine measurement during engine cyclic testing. After calibration the model is used to optimize the housing design.

New housing design concepts are proposed. The articulated asymmetrical volute design has resulted in about 43 % reduction in stresses compared to the baseline design. The X-flange concept resulted in reducing stresses by about 46 %. The new housing design concept is superior by at least 2.5 times increase in life compared to the traditional baseline design.

INTRODUCTION

Engine rating increases and emission trends of retarding fuel timing cause the turbine housing to see severe thermal loads and high engine exhaust temperatures. Future duty cycle challenges for commercial diesel and passenger vehicles for turbocharger applications will potentially result in cases of turbine housing cracking. The cracking can be external and/or internal in nature. The external cracks are considered catastrophic failures since they lead to exhaust gas leaks, which would deem the turbochargers non-functional.

The issues of concern in this paper are the external cracks. In particular, the external cracks at the foot of the turbine inlet flange and at the volute near the V-band location. The volute cracks near the V-band typically initiate close to volute-to-flange connection and propagate circumfrentially parallel to the flow (Figure 1). The inlet flange cracks typically initiate from the volute entry on the inlet flange (Figure 2).

Analytical and experimental methods to investigate the cracking and to guide the designs are adopted (References 1-8). New design modifications at these locations to prevent these problems are investigated and validated.

A technology program was started at Honeywell International Incorporation to address these issues and to develop future turbine housing technology to meet future engine demands of increasing thermal loads. Various tasks towards that goal were started and involved analytical modeling, experimental measuring program and qualification endurance testing. These efforts resulted in significant new housing design enhancements, which were successfully demonstrated on the qualification test, which was developed to accelerate critical duty cycles in operation (Reference 9).

Figure 1: Volute Crack on A Hosing Subjected to Aggressive Field Duty Cycle

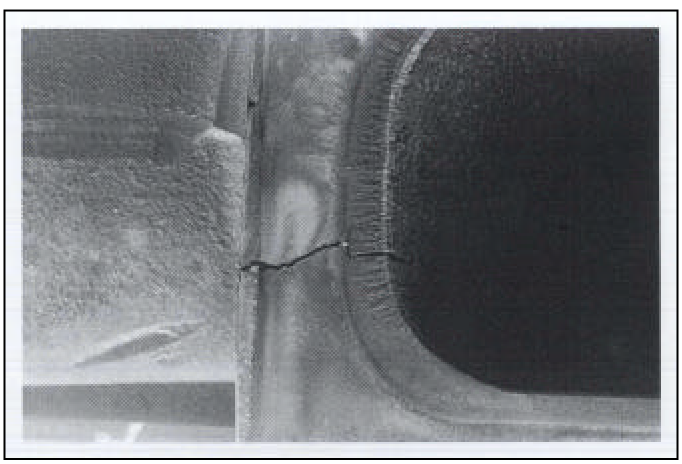


Figure 2: Inlet Flange Crack on Housing Subjected to Aggressive Field Duty Cycle

TECHNICAL APPROACH

Both analytical and experimental techniques are adopted in this work (Reference 1-8). Results of the analytical model were correlated to the experimental measurements for model verification. The experimental measurements were needed to provide boundary conditions for analytical modeling and to provide validation of the analytical results (Reference 1, 8 and 10). The experimental efforts involved transient temperature measurements and thermal imaging on the turbine housing and the center-housing flange during transient thermal 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.

An instrumented housing and an instrumented center-housing flange were utilized on the gas stand to provide correlation between gas stand test environment (Reference 10) 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 a gas stand thermal cycling test is to eliminate the need for the expensive engine endurance testing. Also, the dual gas stand 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 new test procedure for turbine housing thermal endurance testing which is capable of simulating aggressive duty cycle requirements.

The analytical part involved prediction of the thermal stresses induced in the turbine housing as a result of transient thermal cycling and which leads to the turbine housing cracking. In particular, an engine accelerated endurance thermal cycle test was analyzed. Design variants were investigated to optimize the housing geometry.

The approach was first to utilize analytical FE analysis to understand the effect of thermal loading on the turbine housing volute and turbine housings flange to address the root-cause of the external failure at v-band location and at the housing inlet flange. Thermal boundary conditions were obtained on a six-cylinder, in-line engine during accelerated thermal cycling test.

Hardware with the new design enhancements was developed and prepared for both performance and endurance testing. The performance test was compared to baseline design on a back to back type of a test on the performance gas stand. The endurance test was compared to a baseline design in a split type of a test on the dual turbo gas stand.

The housing design involved unique geometrical features at both the inlet flange and volute. Design concepts that address the root-cause of the failure were proposed, analyzed and tested. The first concept addresses the V-band external cracking and involved asymmetrical design of the volute. The volute is articulated to mostly grow radially under transient thermal expansion thus reducing bending around the V-band area. The wall of the volute at the V-band has an elongated almost vertically aligned wall rather than traditional symmetric short bulging walls. Also the transition between casting and machined regions is removed from areas on the volute wall with high stress to low stress areas on the housing.

The second concept addresses the inlet flange cracking and involved a unique X-shaped flange design with a vanishing divider wall at entrance thus eliminating a major driver for flange thermal loading. The flange walls have unique curved walls that result in better distribution of mechanical loads resulting from thermal expansion. The walls are trimmed with uniform thickness to provide better thermal balance and to increase joint flexibility.

In summary, the program objectives were: I) To develop analytical and experimental tools to help investigating cracking issues and guiding new designs; II) To develop new innovative designs to meet future demanding duty cycles and which simultaneously address the root-cause of the failures and meet performance targets; and III) To utilize the developed and verified rig test (Reference 9) for demonstrating and quantifying life enhancements of the new housing design to address external cracking issues at the V-band and inlet flange.

RESULTS AND DISCUSSIONS

In this section we will first discuss the results of engine measurements to provide transient thermal boundary conditions and analytical model calibration. This is followed by the results of the FEA thermal transient analytical modeling of the turbine housing and design optimization. Finally endurance test and performance test results of the new design vs. baseline design are discussed.

ENGINE MEASUREMENTS

Thermal transient measurements cycle 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. Additionally, these results were utilized for calibrating and validating the analytical model. 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 4 shows thermocouples locations on the flange and on the volute area. A total of 27 thermocouples were installed at critical locations of the turbine housing. In addition 3 thermocouples were installed on the flange of the center housing at the V-band. Figure 5 shows a sample of these results for 4 consecutive cycles. The results are repeatable and correlate to what's expected from the accelerated engine thermal cycle test. That thermal differential between the V-band locations and the low temperature center housing connection induces the bending effect at the V-band locations thus resulting in high stresses which is further accentuated by the existence of the machining notch in these areas.

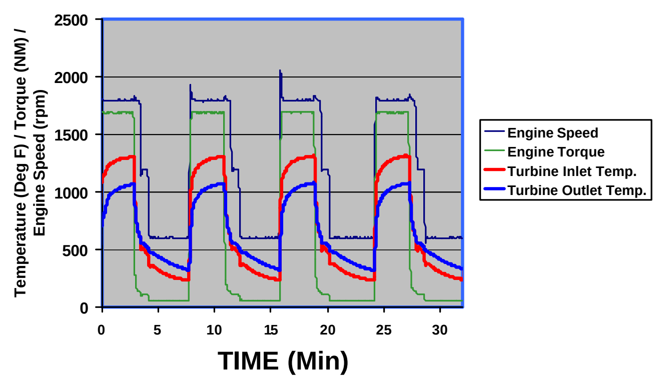


Figure 3: Accelerated Engine Thermal Cycle Test

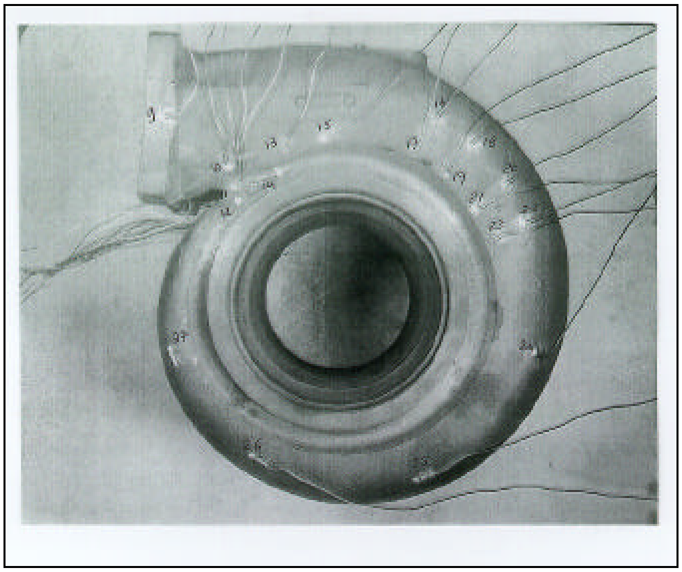


Figure 4: Thermocouples Locations on Turbine Housing.

High temperature strain measurements were also conducted on an in-line, 6 cylinder, 600 HP engine. The measurements were done on a high silicon molybdenum cast iron turbine housing with hourglass flange running through the accelerated engine thermal cycle test. High temperature strain measurements is a difficult task due to the thermal drift of the gauges. Two factors are involved, the differential expansion between the grid support and the grid proper and the change in resistivity with temperature change.

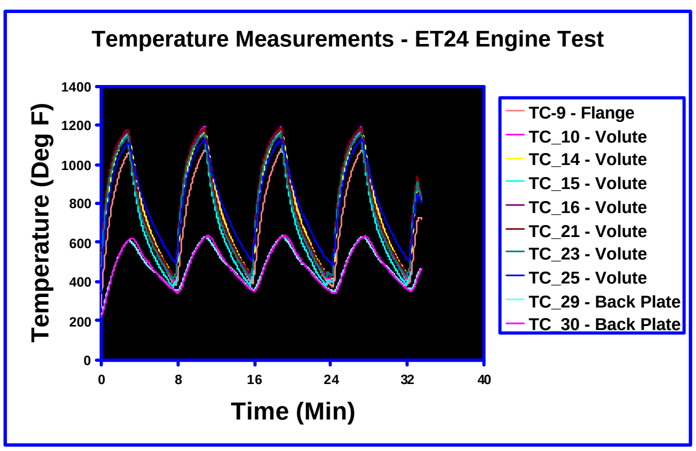


Figure 5: Skin Temperature Profile on Turbine Housing and Back Plate on Accelerated Engine Thermal Cycle.

A special compensation technique for the thermal drift of the gauges at high temperatures was utilized. The technique utilizes a couple of strain gauges and a thermocouple mounted at each location of interest on the turbine housing. Four locations of interest on the turbine housing were instrumented, three at the V-band area (gauges 1,2 and 3) and one on the flange (gauge 4) as shown in Figure 6. The strain gauges were calibrated up to 1200 F while mounted on the turbine housing and utilizing a well-controlled oven. A calibration curve was developed for each gauge location. Linear regression techniques provided good linear fit with R**2 higher than 0.94.

Special instrumentation was adopted to separate the effects of the quasi-static strain levels from the dynamic strain levels. The quasi-static strains are due to the thermal cycling of the turbine housing while the dynamic part is due to vibration induced by the engine.

Figure 7 shows the quasi-static strain levels for 5 consecutive cycles. The cycles are repeatable and the trends are logical and follow what one should expect from such thermal cycles. Results indicate high strain levels at the V-band locations with the highest value around 4500 micro-strain at gauge 1 location. This location is on the volute, near the volute-to-flange connection. These high values indicate that the material has yielded at these locations (yield for this material is defined as .2% yield). For accurate life predictions at these locations plasticity and creep should be included (Reference 11and 12).

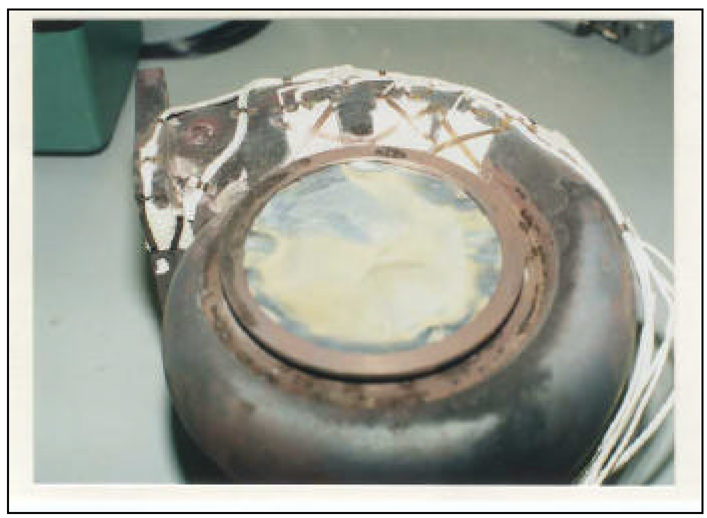


Figure 6: Turbine Housing High Temperature Strain Gauge Locations.

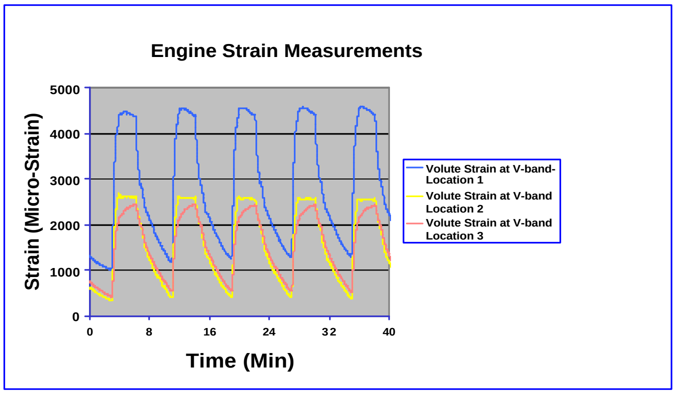


Figure 7: Quasi-Static Strain Profile During Accelerated Engine Thermal Cycle.

ANALYTICAL MODELING

Analytical FEA models provide help to predict the cause of thermal-mechanical cracking of the turbocharger turbine housing. It also provides a method for optimizing the design in the design stage thus reducing the total development cycle time (Reference 3,4 and 13). A 2-D FEA model of the current baseline geometry was built and was correlated to test data. Various design changes were evaluated and optimized for the housing volute and the inlet flange.

The advantage of the 2-D model is the quick turn around of these models as compared to full 3-D thermal transient analysis. The baseline design is compared against modified geometry variants. The 2-D representations at the Volute and the Flange are adequate for this type of optimization. The Stress State on other locations on the housing such as the tongue is quite complex and 3-D in nature. Cracking in such areas has to be addressed with 3-D representation. Though the 3-D analysis approach would yield more accurate absolute values for the stress levels for the transient thermal analysis of the turbine hosing, the 2-D analysis, nevertheless, would give valuable trends for the purpose of comparative analysis and design optimization. A full 3-D on the final geometry is then recommended after understanding the stress trends and finalizing the optimization of the design.

THERMAL BOUNDARY CONDITIONS

Thermal boundary conditions were measured on the turbine housing. The thermal transient model was generated for a representative section through the housing. The measurements were conducted on the engine transient for the accelerated thermal cycle as well as steady state conditions. The material properties utilized in this analysis were input as a function of temperature. The model takes into account both convection and radiation. The first estimation of the heat transfer coefficients were determined utilizing information regarding the flow velocities inside the volute as determined by computational fluid dynamics analysis and turbine gas temperatures measurements of accelerated thermal cycle (Reference 6, 14,15 and 16). Further tuned heat transfer coefficients were determined based on calibration of the model temperature predictions with skin temperature measurements on the turbine housing. The thermal transient analysis was completed with these fine tuned heat transfer coefficients and thermal stresses were determined. The peak stress occurred in the V-band. This agreed with the location of cracking in the hardware.

Figure 8 shows the mesh for the turbine housing. Figure 9 shows the predicted temperature distribution on the volute and the center-housing flange at peak of the ramping-up portion of the thermal cycle. Results show high thermal variation at the volute-center housing flange interface. These large variations cause the housing volute to deform in bending at the V-band. Figure 10 shows comparison of the transient thermal model results with the measured temperatures at 3 representative locations on the turbine housing. Two of these locations are on the volute close to the V-band location (where crack has occurred) and the third is at the center housing flange towards the center housing as shown in Figure 11. Results correlated very well after stabilizing for the first few cycles of the model.

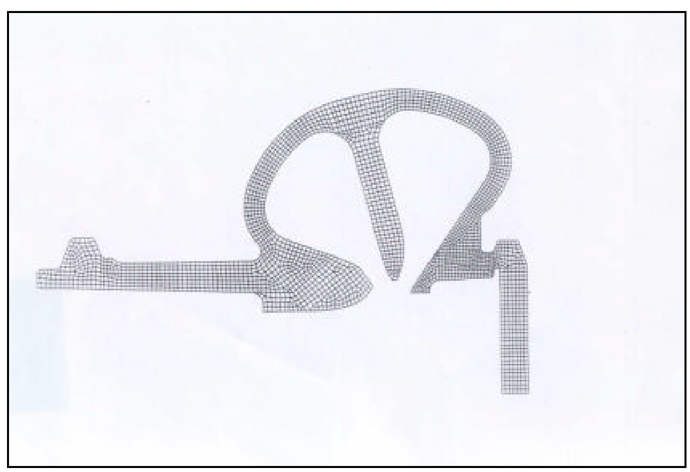


Figure 8: Turbine Housing and Back Plate 2-D FEA Mesh

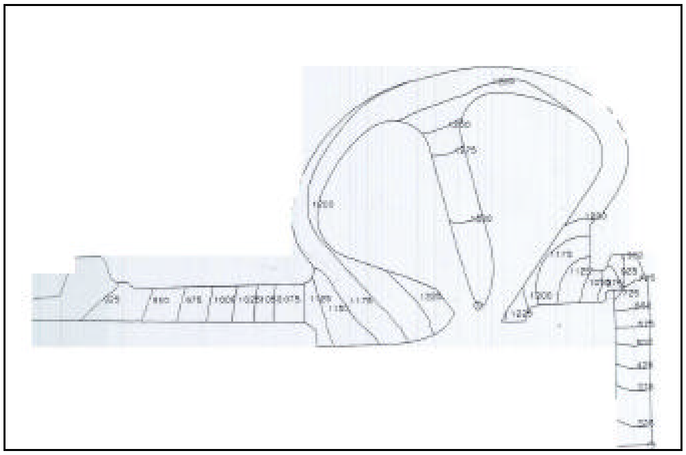
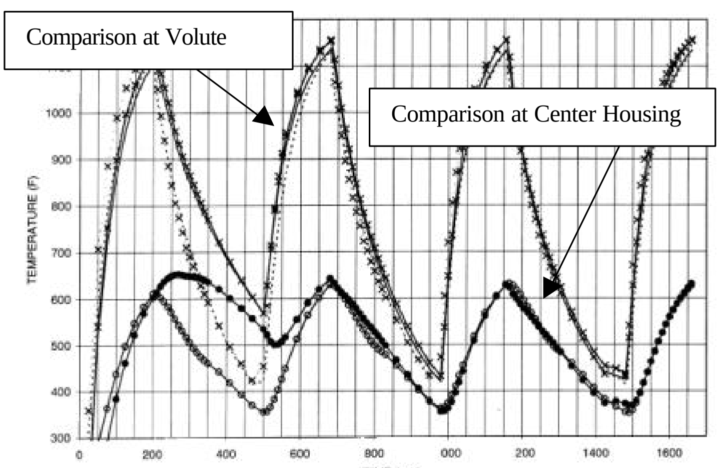


Figure 9: Predicted Temperature Distribution at Peak of Temp. Ramp-up Portion of the Thermal Cycle.

Figure 12 shows the maximum principal stresses at cross section through the volute. The results show high stress at the V-band area in the vicinity of the transition notch. This notch is a result of machining process due to transition between cast and machined regions. The Stress level is around 54 Ksi (372 Mpa). The high stresses are a result of the bending effect at the V-band due to thermal deformations and the stress concentration effects of the existing notch in this high stressed area.



----------- Experimental Data at Volute-Location 1
-----x---- Experimental Data at Volute- Location 2
——o—— Experimental Data at Center Housing
———— Analytical prediction at Volute-Location 1
——x—— Analytical prediction at Volute-Location 2
———— Analytical prediction at Center Housing

Figure 10: Comparison of Thermal Transient Model with Measured Temperatures on the Engine.

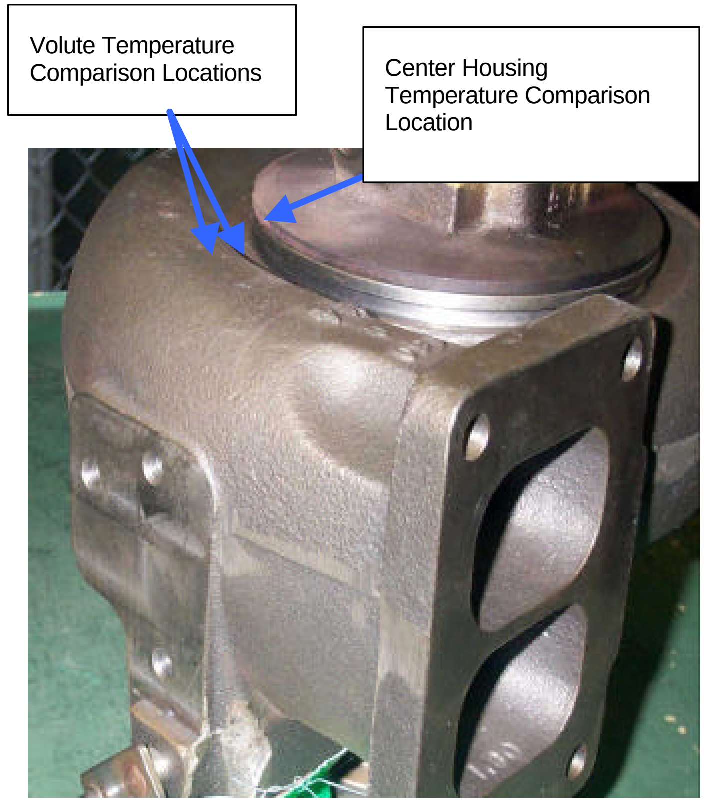


Figure 11: Locations on Housings for Temperature Comparisons of Analytical and Experimental Results.

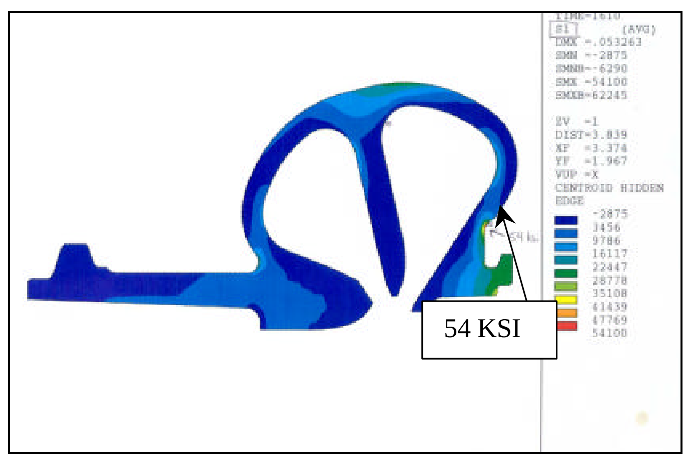


Figure 12: Maximum Principal Stresses at Cross Section through the Volute of Baseline Model.

Figure 13 shows the maximum principal stress at the flange for the baseline model. It shows a maximum stress in the flange of about 45 Ksi (310 Mpa).

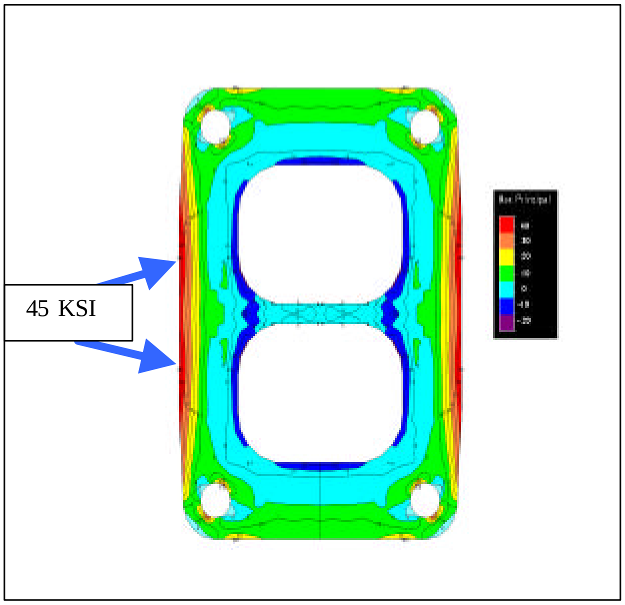


Figure 13: Maximum Principal Stresses on the Flange of Baseline Model.

Several flange geometry and volute to flange connections type have been analyzed to optimize the geometry and reduce these stress levels as further explained in the next section.

OPTIMIZED TURBINE HOUSING DESIGN CONCEPTS

Several design and geometry variants have been conducted. Two areas are optimized using the analytical FEA modeling. These areas are the Volute design at the V-band and the inlet flange design. These areas are addressed in the following sections.

Traditionally for thermal transient cracking problems, thermal gradients can be reduced by correctly thinning the thickness of the walls thus reducing thermally induced mechanical stresses. There should be an optimized thickness to balance between thermally induced mechanical stresses and wall stiffness. Other factors such as burst containment should be taken into consideration. Additionally, removing materials at the right angled joints in the turbine housing between the flange and the divider wall would reduce transient thermal stresses, occurring during rapid cooling and heating of the joints, by reducing the gradients between the higher temperature divider wall and the lower outer wall temperature. Furthermore, such material removal reduces the stiffness of these joints and thus reduces the constraints acting against the thermal growth of the high temperature divider wall. It should be noted that theoretically if a body is subject to elevated temperatures and has been allowed to grow uniformly without any constraints, the body should not experience any cracking problems. The suggested design changes of hour-glass shaped flange (scalloped flange) results in less constraints at the joints and in gradual reduced wall thickness thus potentially helping in reducing flange cracking problems.

More on the subject and such ideas for improving joints design to withstand thermal shocks can be found in the NASA Tech Briefs document titled “improved fillets to withstand Thermal Shocks.” (Reference 17)

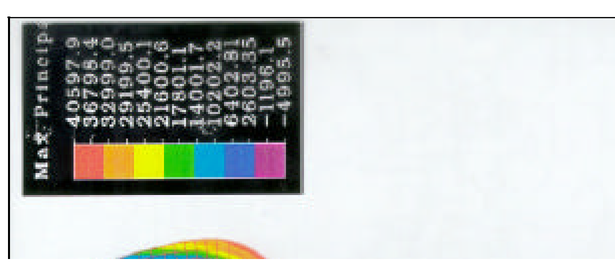
OPTIMIZED VOLUTE DESIGN (ARTICULATED)

An optimized turbine housing design to address the cracking in the V-band area is developed. The volute walls at the V-band connection to center housing extends more vertically and outwards in the radial direction (to compensate for the flow area). The A/R is maintained as the original design at the T-T section and is varied linearly thereafter. Thermal differentials between the volute and the connection to the generally low temperature center housing results in bending action occurring at the V-band location. The current machining of the V-band results in stress concentrations at these high strained areas. Design modifications at this joint could improve the cracking situation.

The design philosophy is to allow the volute to grow almost solely in the radial direction when it is exposed to the thermal loading and thus reducing the bending effect at the V-band as a result of thermal deformations. This design also eliminates the notch in the area of the V-band, which has high thermal strains, by casting this region and removing the transition between the cast and machined region to lower stress regions of the V-band area. In addition, enough spacing has been taken into account to facilitate the machining of the V-band area and to provide enough clearance to place the V-band circumferentially.

Containment consideration was accounted for by maintaining minimum thickness requirement as specified in the design standards and by carrying a similitude analysis for similar turbochargers.

Figure 14 shows the maximum principal stress using the 2-D approach. The maximum principal stress in the V-band vicinity is around 31 Ksi (214 Mpa). This represents a reduction in the maximum stresses of around 43 % as compared to the baseline design, which had maximum stresses of 54 Ksi (372 Mpa).



OPTIMIZED FLANGE DESIGN (X-FLANGE DESIGN)

An optimized turbine inlet flange to address the inlet flange cracking is developed. That effort started with scalloping the flange material on the flange external walls thus resulting in an hourglass shape type of design.

Further design optimization has been carried out with various radical concepts. The divider wall represents a major thermal loading on the flange. The divider wall is one of the hottest sections in the housings directly exposed to high temperature exhaust on both sides. The inlet flange was shaped in an X-shaped flange design thus eliminating a major thermal load driver of the flange due to thermal cycling. In addition inherent in the shape is the scalloping effect of the material on the flange walls as described before. Furthermore, the flange walls were shaped in curved walls to withstand mechanical loads due to thermal expansion. The walls are trimmed with more uniform thickness to provide better thermal balance and increase joint flexibility.

Figure 15 shows the maximum principal stress using the 2-D approach. The maximum principal stress in the flange is around 24 Ksi (165 Mpa). This represents a reduction in the maximum stresses of around 46 % compared to the baseline design, which had maximum stresses of 45 Ksi (310 Mpa).

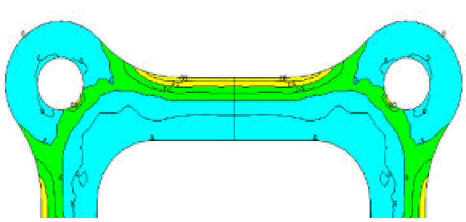


Figure 16 shows the finalized turbine housing design. The housing concept was cast and machined. The material utilized was similar to baseline design material. Several prototypes were acquired for the purpose of endurance qualification testing and Performance testing.

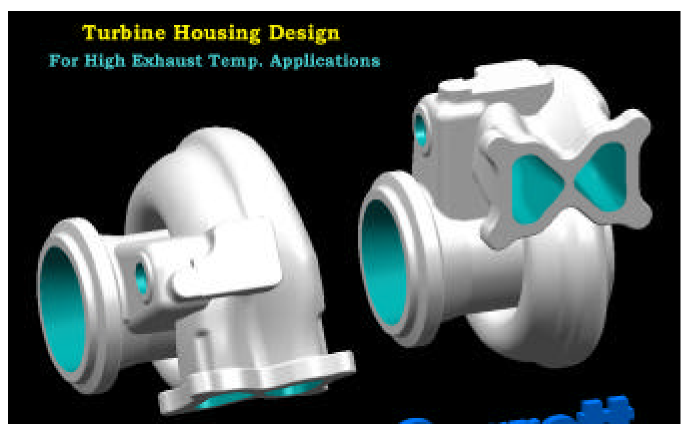


Figure 16: CAD Model of New Turbine Housing Design.

PERFORMANCE TESTING OF OPTIMIZED TURBINE

HOUSING DESIGN

Performance testing of the new optimized turbine housing and the baseline design has been completed on a performance gas stand. Radial clearances were measured on both housings to ensure that they have the same values. The baseline turbocharger was tested first. The turbine housing was replaced by the new design and re-tested. The tests were run back to back to minimize variations in the environment and to ensure the validity of efficiency comparisons. Compressor maps and turbine maps were generated for both the new design and the baseline design. The compressor maps were compared. Figure 17 shows the compressor maps for both cases. The two maps show no significant difference indicating that no variation has occurred on the gas stand when switching the turbine housings.

Turbine housing maps for the new turbine design and the baseline design were compared in Figure 18. The comparison indicates that the maps are close to identical at lower pressure ratios. They start to deviate at higher-pressure ratios around 2. The deviation builds up as the new design exhibit lower efficiency around 1-1.5 points difference at about pressure ration of 3. However, after close examination of the data, it was discovered that the slightly lower efficiency is attributed to slightly higher A/R (A parameter used to indicate the relative size of a turbine housing) for the new design. The pivoting of the efficiency curves is an indication of slight A/R variation between the two housings. This suggests that A/R can be modified to obtain the performance characteristic close to the baseline design.

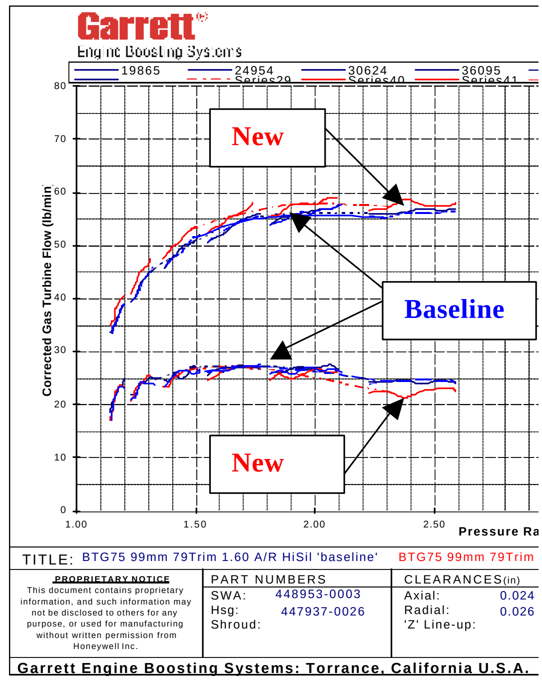
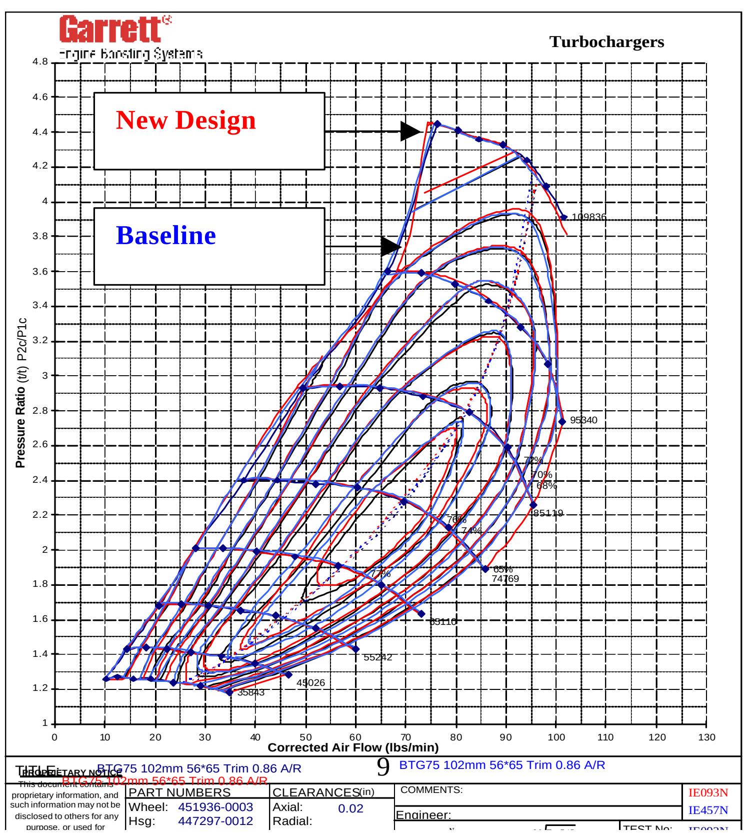


Figure 18: Turbine Map Comparison betwe
Housing Design



ENDURANCE TESTING OF OPTIMIZED TURBINE HOUSING DESIGN

Thermal endurance testing on the developed endurance rig was performed on both the new design and the baseline design. The test was run in a split fashion with a baseline design and a new design running simultaneously on the dual turbo gas stand. The thermal endurance rig had successfully replicated the turbine housing cracking subjected to future aggressive duty cycles in the field, thus eliminating the need to run expensive engine endurance test to qualify the new turbine housing.

The baseline design test had completely failed with external cracking after about 200 hours (about 1500 cycles at 8 minutes per cycle) of testing. After about 50 hours of testing, the baseline design had several cracks initiated on the inlet flanges and on the volute close to volute-to-flange connection near the V-band. Several other cracks were noticed on the divider wall, divider wall at the inlet flange, the tongue and the contour area. These cracks have started approximately at about 50 hours of testing or earlier. During examinations at 100, 150 and 200 hours the cracks at the V-band and the flange continuously grew with additional cycles and propagated to the outer surface thus causing gas leakage. The baseline housing was deemed non-functional and was removed from testing. The cracks replicate the engine testing and field experience for future aggressive duty cycles. It should be noticed that the previous traditional gas stand endurance thermal cycle test, which qualified this housing before, was not capable of mimicking the external cracking which was experienced at the inlet flange and the V band for cycle simulating aggressive potential future duty cycles. Second turbine housing with the new design was mounted in place of the failed baseline housing. Two housings of the same new design continued the test on the gas stand to accumulate more data for the new design to confirm conclusions.

One of the new prototypes had accumulated about 700 hours (about 5375 cycle @8 minutes per cycle) and the second unit had accumulated about 500 hours (about 3750 cycle @8 minutes per cycle) before removing them from the endurance test stand. Both units were still functional before removing them from the gas stand.

None of the new design units had any inlet flange cracking at the end of the testing. Figure 19 shows the inlet flange after 700 hours of testing. The 700-hour unit had a crack, which became slightly visible on the volute after 150 hours of testing and propagated further during the 700 hours test duration. The second 500-hour unit did not have such crack even after completing the 500 hours of testing. Figure 20 shows the volute after 500 hours of testing.

Figure 19: Inlet Flange of New Turbine Housing Design After 700 hours of Gas Stand Endurance Testing.

Figure 20: Volute of New Turbine Housing Design After 500 hours of Gas Stand Endurance Testing.

Internal radial relief cracking at the divider wall had started to develop on both units at about 100-200 hours of testing. However, no divider wall cracking at the inlet flange was observed for either of the new design units.

Results indicate that the endurance life of the new housing design is significantly superior compared to the old traditional design.

CONCLUSION

New engine trends of higher exhaust temperature driven by retarded fuel timing to reduce NOX emissions, will likely cause turbine housings to see heavier thermal transient loads and, as a results, greater likelihood of cracks.

The developed analytical and experimental procedures proved to be successful in investigating cracking issues and guiding new designs with significant life improvements.

The X-flange design reduces thermal stresses by about 46 % compared to the traditional flange designs. The articulated asymmetrical volute design reduces thermal stresses by about 43% compared to the traditional volute design.

The articulated asymmetrical volute design and the X-flange design for turbine housings have proved to be superior design compared to the traditional turbine housing design. The enhancement is at least 2.5 times in housing life at these locations.

No significant performance changes are attributed to the changes in the inlet flange X-design or the articulated volute design.

It is recommended that such new housing design should be implemented on future turbomachinery applications when thermal transient cracking is of concern.

It should be noted that the recommended new design features and the developed analytical and experimental tools could proof to be significantly beneficial to other turbomachinery components such as exhaust manifolds.

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