Durability Analysis of Lightweight Crankshafts Design Using Geometrically Restricted Finite Element Simulation Techniques for Camless Engines

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Abstract

In this study a dynamic simulation was conducted on a crankshaft for a single cylinder four stroke camless Engine. Finite element analysis was performed to obtain the variation of stress magnitude at critical locations. The pressure-volume diagram was used to calculate the load boundary condition in dynamic simulation model, and other simulation inputs were taken from the engine specification chart. The dynamic analysis was done analytically and was verified by simulation in FEA. The load was applied to the FEA model in NASTRAN, and boundary conditions were applied according to the engine mounting conditions. The analysis was done for different engine speeds and as a result critical engine speed and critical region on the crankshaft were obtained. Stress variation over the engine cycle and the effect of torsional load in the analysis were investigated. Results from FEA analysis were verified by strain gages attached to several locations on the crankshaft. Results achieved from aforementioned analysis can be used in fatigue life calculation and optimization of this component.

1. Introduction

Crankshaft is one of the most important moving parts in internal combustion engine. Crankshaft is a large component with a complex geometry in the engine, which converts the reciprocating displacement of the piston into a rotary motion. This study was conducted on a single cylinder 4-stroke diesel engine. It must be strong enough to take the downward force during power stroke without excessive bending. So the reliability and life of internal combustion engine depend on the strength of the crankshaft largely. And as the engine runs, the power impulses hit the crankshaft in one place and then another. The torsional vibration appears when a power impulse hits a crankpin toward the front of the engine and the power stroke ends. If not controlled, it can break the crankshaft.

2. Stresses in Crankshaft

The crankpin is like a built in beam with a distributed load along its length that varies with crank position. Each web like a cantilever beam subjected to
bending & twisting. Journals would be principally subjected to twisting.

- Bending causes tensile and compressive stresses.
- Twisting causes shear stress.
- Due to shrinkage of the web onto the journals, compressive stresses are set up in journals & tensile hoop stresses in the webs.

3. Literature Review

Crankshaft is a large component with a complex geometry in the engine, which converts the reciprocating displacement of the piston to a rotary motion with a four link mechanism. This study was conducted on a single cylinder four stroke cycle engine. Rotation output of an engine is a practical and applicable input to other devices since the linear displacement of an engine is not a smooth output as the displacement is caused by the combustion of gas in the combustion chamber. A crankshaft changes these sudden displacements to a smooth rotary output which is the input to many devices such as generators, pumps, compressors.

A detailed procedure of obtaining stresses in the fillet area of a crankshaft was introduced by Henry et al. [1], in which FEM and BEM (Boundary Element Method) were used. Obtained stresses were verified by experimental results on a 1.9 liter turbocharged diesel engine with Ricardo type combustion chamber configuration. The crankshaft durability assessment tool used in this study was developed by RENAULT. The software used took into account torsional vibrations and internal centrifugal loads. Fatigue life predictions were made using Smith Watson criterion. The procedure developed is such it that could be used for conceptual design and geometry optimization of crankshaft.

Guagliano et al. [2] conducted a study on a marine diesel engine crankshaft, in which two different FEA models were investigated. Due to memory limitations in meshing a three dimensional model was difficult and costly. Therefore, they used a bi-dimensional model to obtain the stress concentration factor which resulted in an accuracy of less than 6.9 percent error for a centered load and 8.6 percent error for an eccentric load. This numerical model was satisfactory since it was very fast and had good agreement with experimental results.

Payer et al. [3] developed a two-step technique to perform nonlinear transient analysis of crankshafts combining a beam-mass model and a solid element model. Using FEA, two major steps were used to calculate the transient stress behavior of the crankshaft; the first step calculated time dependent deformations by a step-by-step integration using the new mark-beta method. Using a rotating beam-mass model of the crankshaft, a time dependent nonlinear oil film model and a model of the main bearing wall structure, the mass, damping and stiffness matrices were built at each time step and the equation system was solved by an iterative method. In the second step those transient deformations were enforced to a solid-element-model of the crankshaft to determine its time dependent stress behavior. The major advantage of using the two steps was reduction of CPU time for calculations. This is because the number of degrees of freedom for performing step one was low and therefore enabled an efficient solution. Furthermore, the stiffness matrix of the solid element model for step two needed only to be built-up once.

In order to estimate fatigue life of crankshafts, Prakash et al. [4] performed stress and fatigue analysis on three example parts belonging to three different classes of engines. The classical method of crankshaft stress analysis (by representing crankshaft as a series of rigid disks separated by stiff weightless shafts) and an FEM based approach using ANSYS code were employed to obtain natural frequencies, critical modes and speeds, and stress amplitudes in the critical modes. A fatigue analysis was also performed and the effect of variation of fatigue properties of the material on failure of the parts was investigated. This was achieved by increasing each strain-life parameter ($\sigma_f$, $\epsilon_f$, $b$ and $c$) by 10% and estimating life. It was shown that strength and ductility exponents have a large impact on life, e.g. a 10% increase of $b$ leads to 93% decrease in estimated life.

A geometrically restricted model of a light automotive crankshaft was studied by Borges et al. [5]. The geometry of the crankshaft was geometrically restricted due to limitations in the computer resources available to the authors. The FEM analysis was performed in ANSYS software and a three dimensional model made of Photo elastic material with the same boundary conditions was used to verify the results. This study was based on static load analysis and investigated loading at a specific crank angle. The FE model results showed uniform stress distribution over the crank, and the only region with high stress concentration was the fillet between the crank-pin bearing and the crank web.

Shenoy and Fatemi [6] conducted dynamic analysis of loads and stresses in the connecting rod component, which is in contact with the crankshaft. Dynamic analysis of the connecting rod is similar to dynamics of the crankshaft, since these components form a slide-crank mechanism and the connecting rod motion applies dynamic load on the crank-pin bearing. Their analysis was compared with commonly
used static FEA and considerable differences were obtained between the two sets of analysis. Shenoy and Fatemi [7] optimized the connecting rod considering dynamic service load on the component. It was shown that dynamic analysis is the proper basis for fatigue performance calculation and optimization of dynamically loaded components. Since a crankshaft experiences similar loading conditions as a connecting rod, optimization potentials of a crankshaft could also be obtained by performing an analytical dynamic analysis of the component.

A literature survey by Zoroufi and Fatemi [8] focused on durability performance evaluation and comparisons of forged steel and cast iron crankshafts. In this study operating conditions of crankshaft and various failure sources were reviewed, and effect of parameters such as residual stress and manufacturing procedure on the fatigue performance of crankshaft were discussed. In addition, durability performance of common crankshaft materials and manufacturing process technologies were compared and durability assessment procedure, bench testing, and experimental techniques used for crankshafts were discussed. Their review also included cost analysis and potential geometry optimizations of crankshaft.

In this paper, first dynamic load analysis of the crankshaft investigated in this study is presented. This includes a discussion of the loading sources, as well as importance of torsion load produced relative to bending load. FEA modeling of the crankshaft is presented next, including a discussion of static versus dynamic load analysis, as well as the boundary conditions used. Results from the FEA model are then presented which includes identification of the critically stressed location, variation of stresses over an entire cycle, and a discussion of the effects of engine speed as well as torsional load on stresses.

4. Materials and Manufacturing Processes

The major crankshaft material competitors currently used in industry are forged steel, and cast iron. Comparison of the performance of these materials with respect to static, cyclic, and impact loading are of great interest to the automotive industry. A comprehensive comparison of manufacturing processes with respect to mechanical properties, manufacturing aspects, and finished cost for crankshafts has been conducted by Zoroufi and Fatemi [9] Nallicheri et al. [10] performed on material alternatives for the automotive crankshaft based on manufacturing economics. They considered steel forging, nodular cast iron, micro-alloy forging, and austempered ductile iron casting as manufacturing options to evaluate the cost effectiveness of using these alternatives for crankshafts.

Metal Forming fundamentals and applications carried out by Altan et al [11] on multi-cylinder crankshaft is considered to have a complex geometry, which necessitates proper work piece and die design according to material forge ability and friction to have the desired geometry. The main objective of forging process design is to ensure adequate flow of the metal in the dies so that the desired finish part geometry can be obtained without any external or internal defects. Metal flow is greatly influenced by part or dies geometry. Often, several operations are needed to achieve gradual flow of the metal from an initially simple shape (cylinder or round cornered square billet) into the more complex shape of the final forging.

5. Failure Analysis of Crankshaft

Fatigue crack growth analysis of a diesel engine forged steel crankshaft was investigated by Guagliano and Vergani [12] and Ferguson et al [13]. They experimentally showed that with geometry like the crankshaft, the crack grows faster on the free surface while the central part of the crack front becomes straighter. Based on this observation, two methods were compared; the first considers a three dimensional model with a crack modeled over its profile from the internal depth to the external surface. In order to determine the stress intensity factors concerning modes I and II a very fine mesh near the crack tip is required which involves a large number of nodes and elements, and a large computational time. The second approach uses two dimensional models with a straight crack front and with the depth of the real crack, offering simpler models and less computational time.

Osman Asi [14] performed failure analysis of a diesel engine crankshaft used in a truck, which is made from ductile cast iron. The crankshaft was found to break into two pieces at the crankpin portion before completion of warranty period. The crankshaft was induction hardened. An evaluation of the failed crankshaft was undertaken to assess its integrity that included a visual examination, photo documentation, chemical analysis, micro-hardness measurement, tensile testing, and metallographic examination. The failure zones were examined with the help of a scanning electron microscope equipped with EDX facility. Results indicate that fatigue is the dominant mechanism of failure of the crankshaft.

Another crack detection method was introduced by Baxter [15]. He studied crack detection using a modified version of the gel electrode technique. This technique could identify both the primary fatigue
cracks and a distribution of secondary sites of less severe fatigue damage. The most useful aspect of this study is that the ELPO film can be applied before or after the fatigue test, and in both cases, the gel electrode technique is successful at detecting fatigue damage. As can be seen, a fatigue crack of length 2.2 cm exists along the edge of the fillet, which the markings from this technique clearly identify.

6. Design Considerations

An analysis of the stress distribution inside a crankshaft crank was studied by Borges et al. [16]. The stress analysis was done to evaluate the overall structural efficiency of the crank, concerned with the homogeneity and magnitude of stresses as well as the amount and localization of stress concentration points. Due to memory limitations in the computers available, the crank model had to be simplified by mostly restricting it according to symmetry planes. In order to evaluate results from the finite element analysis a 3D photo elasticity test was conducted.

The influence of the residual stresses induced by the fillet rolling process on the fatigue process of a ductile cast iron crankshaft section under bending was studied by Chien et al.[17] using the fracture mechanics approach. They investigated fillet rolling process based on the shadowgraphs of the fillet surface profiles before and after the rolling process in an elastic-plastic finite element analysis with consideration of the kinematic hardening rule. A linear elastic fracture mechanics approach was employed to understand the fatigue crack propagation process by investigating the stress intensity factors of cracks initiating from the fillet surface.

Steve Smith [18] provided a simple method to understand how well a crankshaft can cope with power delivery by monitoring crankcase deflection during powered dyno runs. The data made available supports engineering decisions to improve the crankshaft design and balance conditions; this reduces main bearing loads, which lead to reduced friction and fatigue, releasing power, performance and reliability. As the power and speed of engines increase, crankshaft stiffness is critical. Model solutions do not give guaranteed results; Empirical tests are needed to challenge model predictions. Residual imbalances along the length of the crankshafts are crucial to performance. Utilizing crankcase deflection analysis to improve crankshaft design and engine performance. Sunit Mhasade and Parasram Parihar [19] presented the design of crankshaft used in TATA Indica Vista car. The model selected is Quadrajet Aura. The engine runs on 4 cylinders 1248 cc, Inline Diesel, 475IDI engine, 75 PS (55KW)@ 4000 rpm, Compressor Ignition (CI) Engine. An analytical tool for the efficient analysis of crankshaft design has been developed by Terry M. Shaw [20] Cummins Engine Co., Inc. Ira B. Richter - Cummins Engine Co., Inc. [21]. Finite element models are generated from a limited number of key dimensions which describe a family of crankshafts. These models have been verified by stress and deflection measurements on several crankshaft throws.

7. Durability assessment on Crankshaft

Durability assessment of crankshafts was carried out by Zoroufi, M. and Fatemi, A. [22] includes material and component testing, stress and strain analysis, and fatigue or fracture analysis. Material testing includes hardness, monotonic, cyclic, impact, and fatigue and fracture tests on specimens made from the component or from the base material used in manufacturing the component. Component testing includes fatigue tests under bending, torsion, or combined bending-torsion loading conditions. Dynamic stress and strain analysis must be conducted due to the nature of the loading applied to the component. Nevertheless, performing transient analysis on a three dimensional solid model of a crankshaft is costly and time consuming.

Payer et al. [23] developed a two-step technique to perform nonlinear transient analysis of crankshafts combining a beam mass model and a solid element model. Using FEA, two major steps are used to calculate the transient stress behavior of the crankshaft; the first step is the calculation of time dependent deformations by a step-by-step integration. Using a rotating beam-mass-model of the crankshaft, a time dependent nonlinear oil film model and a model of the main bearing wall structure, the mass damping, and stiffness matrices are built at each time step. The system of resulting equations is then solved by an iterative technique.

Henry et al. [24] presented a procedure to assess crankshaft durability. This procedure consists of four main steps. The first step is modeling and load preparation that includes mesh generation, calculation of internal static loads (mass), external loads (gas and inertia) and torsional dynamic response due to rotation. The second step is the finite element method calculation including generating input files for separate loading conditions. Third step is the boundary condition file generation. The final step involves the fatigue safety factor determination. This procedure was implemented for a nodular cast iron diesel engine crankshaft.

8. Dynamic load analysis
9. Dynamic load analysis

Dynamic loading analysis by Montazersadgh, F. H. and Fatemi, A [21] of the crankshaft results in more realistic stresses whereas static analysis provided an overestimate results. Accurate stresses are critical input to fatigue analysis and optimization of the crankshaft. There are two different load sources in an engine; inertia and combustion. These two load source cause both bending and torsional load on the crankshaft. The maximum load occurs at the crank angle of 355 degrees for this specific engine. At this angle only bending load is applied to the crankshaft. Superposition of FEM analysis results from two perpendicular loads is an efficient and simple method of achieving stresses at different loading conditions according to forces applied to the crankshaft in dynamic analysis. Experimental and FEA results showed close agreement, within 7% difference. The results indicate non-symmetric bending stresses on the crankpin bearing, whereas using analytical method predicts bending stresses to be symmetric at this location. The lack of symmetry is a geometry deformation effect, indicating the need for FEA modeling due to the relatively complex geometry of the crankshaft.

Shenoy and Fatemi [25] conducted dynamic analysis of loads and stresses in the connecting rod component, which is in contact with the crankshaft. Dynamic analysis of the connecting rod is similar to dynamics of the crankshaft, since these components form a slide-crank mechanism and the connecting rod motion applies dynamic load on the crank-pin bearing. Their analysis was compared with commonly used static FEA and considerable differences were obtained between the two sets of analysis.

A system model for analyzing the dynamic behavior of an internal combustion engine crankshaft is described by Zissimos P. Mourelatos [26]. The model couples the crankshaft structural dynamics, the main bearing hydrodynamic lubrication and the engine block stiffness using a system approach. A two-level dynamic sub structuring technique is used to predict the crankshaft dynamic response based on the finite-element method. The dynamic sub structuring uses a set of load-dependent Ritz vectors. The main bearing lubrication analysis is based on the solution of the Reinhold’s equation. Comparison with experimental results demonstrates the accuracy of the model.

10. Computer aided analysis of crankshaft

Development of an engine crankshaft in a framework of computer-aided innovation by A. Albers et al. [27] describes the conceptual framework of a general strategy for developing an engine crankshaft based on computer-aided innovation, together with an introduction to the methodologies from which our strategy evolves. It begins with a description of two already popular disciplines, which have their roots in computer science and natural evolution: evolutionary design (ED) and genetic algorithms (GAs). A description of some optimization processes in the field of mechanical design is also presented. The main premise is the possibility to optimize the imbalance of a crankshaft using tools developed in this methodology. This study brings together techniques that have their origins in the fields of optimization and new tools for innovation.

A review of Crankshaft Lightweight Design and Evaluation based on Simulation Technology is presented by Sheng Su, et al. [28]. In order to reduce fuel consumption and emission and improve efficiency, it is essential to take lightweight design into consideration in concept design phase and layout design phase. Crankshaft is one of the most important components in gasoline engine, and it is related to durability, torsional vibration, bearing design and friction loss, therefore lightweight crankshaft must meet the needs to see to it that the final design is satisfactory.

An advanced method for the calculation of crankshafts and sliding bearings for reciprocating internal combustion engines is presented by Elena Galindo et al. [29]. The indeterminate method provides a valid tool for the design of crankshafts and sliding-bearings, and enables calculation to come closer to real performance of same. In general, the results furnished by the indeterminate method allow for use of a wider range of criteria in the choice of fundamental design parameters. Other aspects not taken into account in this model, such as main bearing elastic deformation or cylinder block stiffness, would make for a more accurate picture of the integrated performance of the crankshaft-bearing unit as a whole. Chunming Yang et al. [30] are proposed for design optimization on crankshaft by new particle swarm optimization method (NPSO). It is compared with the regular particle swarm optimizer (PSO) invented based on four different benchmark functions. Particle swarm optimization is a recently invented high-performance optimizer that is very easy to understand and implement. It is similar ways to genetic algorithms or evolutionary algorithms, but requires less computational bookkeeping and generally only a few lines of code. Each particle studies its own previous best solution to the optimization problem, and its group’s previous best, and then adjusts its position accordingly. The optimal value will be found by repeating this process.
Humberto Aguayo Téllez et al.[31] is described for determining the design unbalance of crankshafts and also the recommended procedure for a balanced design strategy on Computer aided innovation of crankshafts using Genetic Algorithms. The use of a search tool for solutions is suggested based on Genetic Algorithms (GA). GAs have been used in different applications, one of them is the optimization of geometric shapes, a relatively recent area with high research potential. The interest towards this field is growing, and it is anticipated that in the future mechanical engineering will be an area where many applications of shape optimization will be widely applied.

11. Cost reduction

The automotive crankshaft, one of the more metal intensive components in the engine, provides an attractive opportunity for the use of alternate materials and processing routes. A systematic cost estimation of crankshafts is provided in the work of Nallicheri et al. [10]. Dividing the cost of crankshafts into variable and fixed cost, they evaluate and compare the production cost of crankshafts made of nodular cast iron, austempered ductile iron, forged steel, and micro alloyed forged steel. The common variable cost elements are named as the costs of material, direct labor, and energy. The common elements of fixed cost are named as the costs of main machine, auxiliary equipment, tooling, building, overhead labor, and maintenance.

A study was performed to examine the cost reduction opportunities to offset the penalties associated with forged steel, with raw material and machine inability being the primary factors evaluated by Hoffmann et al. [32] Materials evaluated in their study included medium carbon steel SAE 1050 (CS), and medium carbon alloy steel SAE 4140 (AS); these same grades at a sulfur level of 0.10%, (CS-HS and AS-HS); and two micro-alloy grades (MA1 and MA2). The micro-alloy grades evaluated offered cost reduction opportunities over the original design materials. The micro-alloy grade could reduce the finished cost by 11% to 19% compared to a quenched and tempered alloy steel.

12. Major Consideration for a Crankshaft

- Fatigue is the dominant mechanism of failure of the crankshaft.
- Residual imbalances along the length of the crankshafts are crucial to performance. Utilizing crankcase deflection analysis to improve crankshaft design and engine performance.
- Dynamic stress and strain analysis must be conducted due to the nature of the loading applied to the component such as crankshaft.
- Accurate stresses are critical input to fatigue analysis and optimization of the crankshaft.

13. Crankshaft Durability analysis using FEA

In this report the results of durability analysis of crank shaft of camless engine is shown using FEA software. In this process the crank shaft is analyzed for various static loads and undergone for durability test for critical loads in order to determine the approximate cycle life of the shaft. The material of the crankshaft disc and shaft is SAE 1144 stress proof. This crankshaft disc and shaft is specially designed for cam less engine. After assembly we have to TIG weld the end of the shaft to the disc OR drill a 1/8” hole 5/16” deep at the interface between shaft and the disc and press fit a 0.127” diameter pin into the hole to prevent the disc from slipping on the shaft. The crankshaft bearing provides 0.016” of clearance between the crankshaft disc and the crankcase end plate. We have to mill slots 5/64” deep with 1/8” or 5/32” ball end mill for flywheel set screws and undercut 0.005” for timing disc set screws.

Brief load conditions and model is shown in the figure-2 below: In this report the results of durability analysis of crank shaft is shown using FEA software. In this process the crank shaft is analyzed for various static loads and undergone for durability test for critical loads in order to determine the approximate cycle life of the shaft.

14. Structural Steel - Constants

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7850 kg m^-3</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>1.2e-005 C^-1</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>434 J kg^-1 C^-1</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>60.5 W m^-1 C^-1</td>
</tr>
<tr>
<td>Resistivity</td>
<td>1.7e-007 ohm m</td>
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<tr>
<td>Compressive Ultimate Strength</td>
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<tr>
<td>Compressive Yield Strength</td>
<td>2.5e+1008 pa</td>
</tr>
<tr>
<td>Tensile Yield Strength</td>
<td>2.5e+008 pa</td>
</tr>
</tbody>
</table>
1. **Loading**: The crankshaft is loaded with a load of 500N by keeping one of its ends as fixed constrained.

![Crankshaft with load](image)

**Fig: 2. Loading**
2. Meshing

![Image of meshed model](image1)

**Fig: 3. Meshing**

3. Stress: Von-Mises

![Image of stress distribution](image2)

**Fig: 4. Stress: Von-Mises**
4. **Durability:** Here Smith Watson tool has been utilized

![Fig: 5. Durability](image1)

5. **Fatigue Life**

![Fig: 6. Fatigue Life](image2)
6. Fatigue damage

![Fatigue damage diagram](image1)

**Fig: 7. Fatigue damage**

7. Strength Safety Factor

![Strength Safety Factor diagram](image2)

**Fig: 8. Strength Safety Factor**
8. Fatigue safety factor

Fig: 9. Fatigue safety factor

9. Fatigue Failure Index

Fig: 10. Fatigue failure index
15. Conclusions

The following conclusions could be drawn from this study:

1. Dynamic loading analysis of the crankshaft results in more realistic stresses whereas static analysis provides an overestimate results. Accurate stresses are critical input to fatigue analysis and optimization of the crankshaft.

2. There are two different load sources in an engine; inertia and combustion. These two load source cause both bending and torsional load on the crankshaft.

3. The maximum load occurs at the crank angle of 352 degrees for this specific engine. At this angle only bending load is applied to the crankshaft.

4. Considering torsional load in the overall dynamic loading conditions has no effect on von Mises stress at the critically stressed location. The effect of torsion on the stress range is also relatively small at other locations undergoing torsional load. Therefore, the crankshaft analysis could be simplified to applying only bending load.

5. Critical locations on the crankshaft geometry are all located on the fillet areas because of high stress gradients in these locations which result in high stress concentration factors.

6. Superposition of FEM analysis results from two perpendicular loads is an efficient and simple method of achieving stresses at different loading conditions according to forces applied to the crankshaft in dynamic analysis.

7. Experimental and FEA results showed close agreement, within 7% difference. These results indicate non-symmetric bending stresses on the crankpin bearing, whereas using analytical method predicts bending stresses to be symmetric at this location. The lack of symmetry is a geometry deformation effect, indicating the need for FEA modeling due to the relatively complex geometry of the crankshaft.

References


[19] Sunit Mhasade and Parasram Parihar “Design of crankshaft” NITIE students


