Crankshaft Design and Optimization- A Review

Amit Solanki¹, Ketan Tamboli², M.J. Zinjuwadia³

¹ P.G. Student, Mechanical Engg. Deptt. B V M Engg. College, V.V.Nagar, INdia
² Asst. Professor, Mechatronics Engg. Deptt. GCET, V.V.Nagar, INdia
³ Associate Professor, Mechanical Engg. Deptt. B V M Engg. College, V.V.Nagar, INdia

¹solanki.foru@yahoo.com
²ketantamboli2000@yahoo.com
³mjzbvm@gmail.com

Abstract— The performance of any automobile largely depends on its size and working in dynamic conditions. The design of the crankshaft considers the dynamic loading and the optimization can lead to a shaft diameter satisfying the requirements of automobile specifications with cost and size effectiveness. The review of existing literature on crankshaft design and optimization is presented. The materials, manufacturing process, failure analysis, design consideration etc. of the crankshaft are reviewed here.

Keywords— crankshaft design, optimization, dynamic loading

I. INTRODUCTION

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. Since the crankshaft experiences a large number of load cycles during its service life, fatigue performance and durability of this component has to be considered in the design process. Design developments have always been an important issue in the crankshaft production industry, in order to manufacture a less expensive component with the minimum weight possible and proper fatigue strength and other functional requirements. These improvements result in lighter and smaller engines with better fuel efficiency and higher power output.

The crankshaft consists of the shaft parts which revolve in the main bearings, the crankpins to which the big ends of the connecting rod are connected, the crank arms or webs (also called cheeks) which connect the crankpins and the shaft parts. The crankshaft main journals rotate in a set of supporting bearings ("main bearings"), [Fig.1.1] causing the offset rod journals to rotate in a circular path around the main journal centers, the diameter of that path is the engine "stroke": the distance the piston moves up and down in its cylinder. The big ends of the connecting rods ("conrods") contain bearings ("rod bearings") which ride on the offset rod journals.

II. 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.[Fig.1.2]

1. Bending causes tensile and compressive stresses.
2. Twisting causes shear stress.
3. Due to shrinkage of the web onto the journals, compressive stresses are set up in journals & tensile hoop stresses in the webs.
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 (23). Nallicheri et al. (14) 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. (1) on multi-cylinder crankshaft is considered to have a complex geometry, which necessitates proper workpiece and die design according to material forgeability 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.

FAILURE ANALYSIS OF CRANKSHAFT

Fatigue crack growth analysis of a diesel engine forged steel crankshaft was investigated by Guagliano and Vergani (8) and Guagliano et al. (9). 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 (15) 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 (3). 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.

DESIGN CONSIDERATIONS

An analysis of the stress distribution inside a crankshaft crank was studied by Borges et al. (4). 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 photoelasticity 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. (5) 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 (19) 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 - NITIE (20) 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 (21) Cummins Engine Co., Inc. Ira B. Richter - Cummins Engine Co., Inc. (13). 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.

VI. 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. (16) 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 massdamping, and stiffness matrices are built at each time step. The system of resulting equations is then solved by an iterative technique.

Henry et al. (10) 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.

VII. DYNAMIC LOAD ANALYSIS

Dynamic loading analysis by Montazersadgh, F. H. and Fatemi, A (13) 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 (17) 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 (24). 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 substructuring technique is used to predict the crankshaft dynamic response based on the finite-element method. The dynamic substructuring 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.

VIII. COMPUTER AIDED ANALYSIS OF CRANKSHAFT

Development of an engine crankshaft in a framework of computer-aided innovation by A.Albers et al.(2) 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. (18) 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.(7)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. (6) 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 evo-lutionary 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.(12) is described for determining the design unbalance of crankshafts and also the recommended procedure for a balanced design strategy on Computer aided innovaton 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.

IX. 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. (14). 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 machinability being the primary factors evaluated by Hoffmann et al.(11) 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.

CONCLUSIONS

For a crankshaft following are the major consideration:
1. Comparative study needs to be applied for the selection of material and manufacturing process so as to have cost effectiveness and shape with fewer defects respectively.
2. In the crankshaft, the crack grows faster on the free surface while the central part of the crack front becomes straighter.
3. Fatigue is the dominant mechanism of failure of the crankshaft.
4. Residual imbalances along the length of the crankshafts are crucial to performance. Utilizing crankcase deflection analysis to improve crankshaft design and engine performance.
5. Dynamic stress and strain analysis must be conducted due to the nature of the loading applied to the component such as crankshaft.
6. Accurate stresses are critical input to fatigue analysis and optimization of the crankshaft.

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REFERENCES

[6] Chunming Yang and Dan Simon “A New Particle Swarm Optimization Technique for crankshaft” Electrical and Computer Engineering Department Cleveland State University Cleveland, Ohio 44115 c.yang@csuohio.edu

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