CAE Analysis of Crankshaft for Testing Dynamic Loads for Reducing Cost & Weight

Salim Ahmed, Tasmeem Ahmad Khan

Abstract

This study was conducted on a single cylinder four stroke cycle engine. Two different crankshafts from similar engines were studied in this research. The finite element analysis was performed in four static steps for each crankshaft. Stresses from these analyses were used for superposition with regards to dynamic load applied to the crankshaft. Further analysis was performed on the forged steel crankshaft in order to optimize the weight and manufacturing cost.

Key words: FEA,CAE Analysis, Dynamic Load analysis, cost optimization, Weight reduction, Crank shaft, Crankshaft Analysis, Cost and weight reduction

I. Background

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Crankshaft experiences large forces from gas combustion. This force is applied to the top of the piston and since the connecting rod connects the piston to the crankshaft, the force will be transmitted to the crankshaft. The magnitude of the force depends on many factors which consists of crank radius, connecting rod dimensions, and weight of the connecting rod, piston, piston rings, and pin. Combustion and inertia forces acting on the crankshaft cause two types of loading on the crankshaft structure; torsional load and bending load.

This research was performed on crankshafts from single cylinder engines. However, since the basis of analysis are the same for multi-cylinder engines, the procedures used could be modified and implemented for crankshafts from other types of engines.

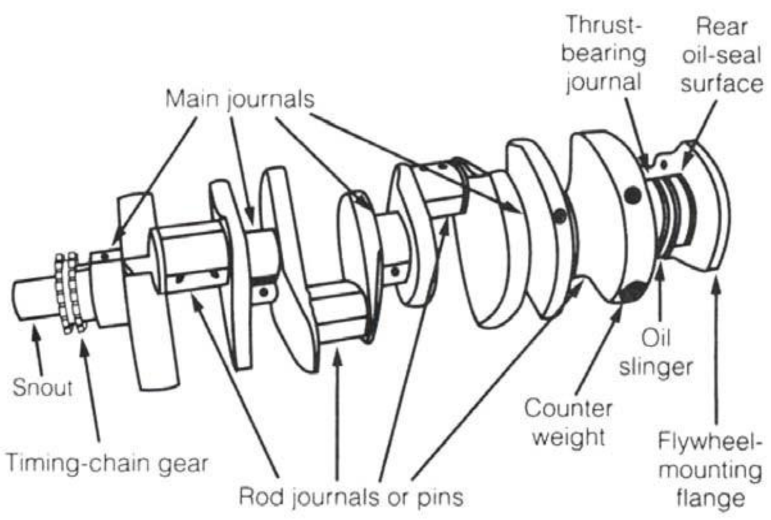

Figure 1.1Typical crankshaft with main journals that support the crankshaft in the engine block. Rod journals are offset from the crankshaft centerline (Halderman and Mitchell).

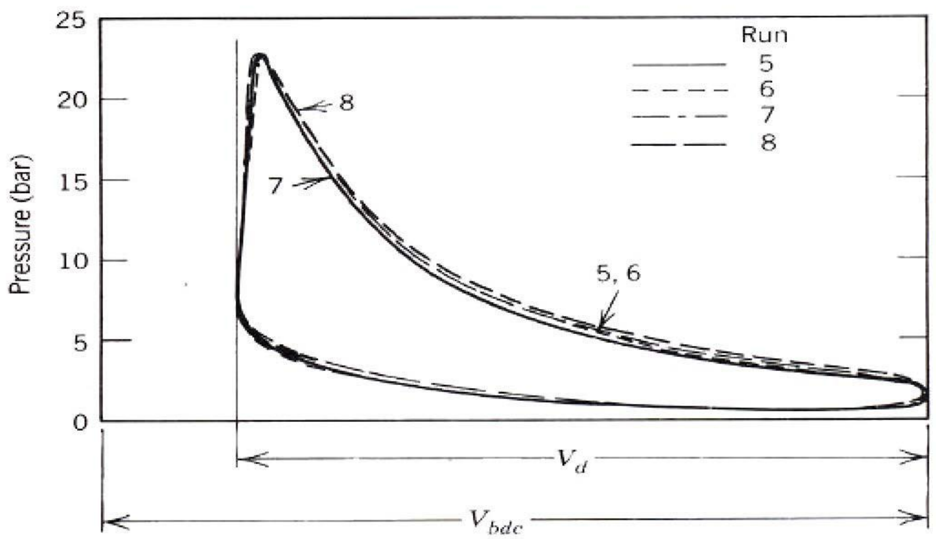

Figure 1.2 P-V diagram at constant delivery ratio. Curve 5 is for 900 rev/min, curve 6 for 1200 rev/min, curve 7 for 1500 rev/min, and curve 8 for 1800 rev/min (Ferguson, 1986).

Crankshaft side view

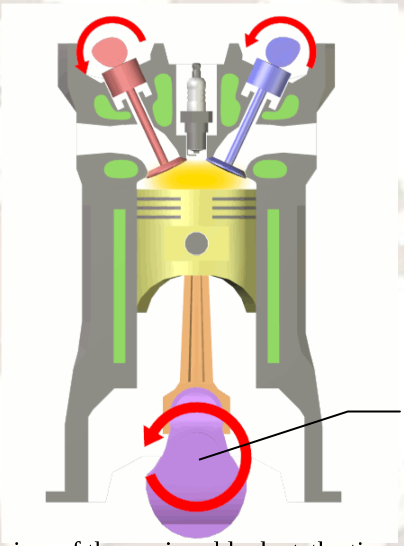

Figure 1.3 Side view of the engine block at the time of combustion

II. 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 (2005).

This Section discusses forging and casting processes as the two competing manufacturing processes in crankshaft production industry. Influencing parameters in both processes are detailed. Finally, the forged steel and the cast iron products are compared in terms of material properties and manufacturing processes.

III. Forging Process and the Influencing Parameters

Forging is the term for shaping metal by plastic deformation. Cold forging is done at low temperatures, while conventional hot forging is done at high temperatures, which makes metal easier to shape. Cold forgings are various forging processes conducted at near ambient temperatures, such as bending, cold drawing, cold heading, coining, and extrusion to produce metal components to close tolerances and net shape Warm forging is a modification of the cold forging process where the workpiece is heated to a temperature significantly below the typical hot forging temperature, ranging from 500º C to 750º C Compared with cold forging, warm forging has the potential advantages of reduced tooling loads, reduced press loads, increased steel ductility, elimination of need to anneal

IV. Dynamic Load Analysis of the Crankshaft

The crankshaft experiences a complex loading due to the motion of the connecting rod, which transforms two sources of loading to the crankshaft. The main objective of this study was the optimization of the forged steel crankshaft which requires accurate magnitude of the loading on this component that consists of bending and torsion. The significance of torsion during a cycle and its maximum compared to the total magnitude of loading should be investigated to see if it is essential to consider torsion during loading or not. In addition, there was a need for obtaining the stress variation during a loading cycle and this requires FEA over the entire engine cycle.

The main objective of this chapter is to determine the magnitude and direction of the loads that act on the bearing between connecting rod and crankshaft, which was then used in the FEA over an entire cycle. An analytical approach was used on the basis of a single degree of freedom slider crank mechanism. MATLAB programming was used to solve the resulting equations.

The analytical approach was solved for a general slider crank mechanism which results in equations that could be used for any crank radius, connecting rod geometry, connecting rod mass, connecting rod inertia, engine speed, engine acceleration, piston diameter, piston and pin mass, pressure inside cylinder diagram, and any other variables of the engine. This analytical approach also helped to verify that the inputs in the ADAMS View software were correct. However, since changing variables in the analytical approach using MATLAB programming code was more convenient, the results of ADAMS View software were used as verification of the analytical solutions.

V. FEA with Dynamic Loads

There are two different approaches for applying the loads on the crankshaft to obtain the stress time history. One method is to run the FE model many times during the engine cycle or at selected times over 720° by applying the magnitude of the load with its direction in a way that the loading could define the stress-time history of the component. Another approach to obtain stresses at different locations at different times during a cycle is by superposition of the basic loading conditions. This involves applying a unit load in the basic conditions and then scaling the stresses from each unit load according to the dynamic loading. Then similar stress components are added together. In this study both approaches were used for the engine speed of 3600 rpm to verify that results from both approaches are the same. After verification of results, the superposition approach was used by developing a code in Excel spread sheet to perform the necessary calculation and obtain the results for the stresses at different crankshaft angles.

Justification for selecting some locations over 720° was according to peaks and valleys of load variation. Three different graphs were used for selecting proper points to cover the entire cycle; bending, torsion, and total load magnitude. Figure 3.18 shows the variation of these loads versus crank angle. Selected points are labeled in this figure and the reason of selecting each point is indicated as follows:

a. Beginning of the cycle

b. A peak of the bending load c. Valley of the bending load d. Bending load of zero

e. Peak of torsional load

f. Peaks of bending load and total load magnitude g. A valley of torsional load

h. Bending load of zero

i. A valley of total load magnitude j. A valley of bending load

k. Selected to have smooth connectivity between the points before and after

l. A valley of total load magnitude and a peak of bending load

The same locations could be identified in the load history diagram of the crankshaft at other engine speeds. However, only engine speed of 2000 rev/min was selected for verification of results.

VI. Cost Analysis

Cost analysis is based on geometry changes and weight, modification in manufacturing process and the use of alternative material. The optimized geometry requires redesign and remanufacturing the forging dies used. The geometry parameters that influence machining and the final cost of the component include the increase of drilling process, because the drilled holes at the back of the crankshaft and the crankpin are redesigned to have larger diameters, and the bore at the back is modified to have more depth than the original bore.

Adding residual stress by fillet rolling process is a parameter in the manufacturing process that will add to the cost of the finished component.

Nallicheri et al. (1991) studied material alternatives for the automotive crankshaft based on manufacturing economics. The approach they used in technical cost modeling is to separate the different cost elements and estimate each one separately. As defined in their study, the costs are separated in two elements of variable and fixed costs. Variable cost elements are the contribution to piece cost whose values are independent of the number of elements produced. And in contrast with the variable costs, the fixed costs are those elements of piece cost which are a function of the annual production volume. Assumptions made for the cost analysis modeling are tabulated in Tables 1,2 and 3. These tables show manufacturing assumptions used as the basis of cost estimation for a

32.6 lb crankshaft using hot rolled steel bar and microalloyed steel. The major difference between the assumptions in the case of hot rolled steel forging and microalloy forging were those of the die life and material cost. A minor improvement in die life was assumed owing to the enhanced formability of microalloyed steel. In case of microalloy forging, the quench and temper step was eliminated, resulting in cost savings

Table 1 Typical mechanical and fatigue properties of Ti-added controlled-cooled 35MV7 steel (Pichard et al., 1993) and AISI 1045 steel (Williams and Fatemi, 2007).

Steel	Heat Treatment	Ultimate Strength (MPa)	Yield Strength (MPa)	Fatigue Strength (MPa)	Percent Elongation (%)	Percent Reduction in Area (%)
AISI 1045	Q + T	827	625	395	54	58
35MV7	Cont. Cooled	925	630	478	15	50

Table 2Manufacturing assumptions for a forged steel crankshaft weighing 32.6 lbs (Nallicheri, 1991).

Part Weight	32.6 lbs
Material	Hot Rolled Steel Bar (4130)
Die Life (parts)	15,000
Material Cost	$0.22/lb
Forging Impressions	2
Cavities/impression	1
Maintenance	4%
Building Area	25,000 sq. ft.

Table 3 Manufacturing assumptions for a microalloyed steel forging crankshaft weighing 32.6 lbs (Nallicheri, 1991).

Part Weight	32.6 lbs
Material	Microalloy Steel
Die Life (parts)	20,000
Material Cost	$0.25/lb
Forging Impressions	2
Cavities/impression	1
Maintenance	4%
Building Area	25,000 sq. ft.

VII. Summary and Conclusions

A forged steel and a ductile cast iron crankshaft were chosen for this study, both of which belong to similar single cylinder four stroke air cooled gasoline engines.

The following conclusions can be drawn from the analysis conducted in this study:

1. Dynamic loading analysis of the crankshaft results in more realistic stresses whereas static analysis provides overestimated 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. 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.

3. 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.
4. Superposition of FEM analysis results from two perpendicular loads is an efficient and simple method of achieving stresses for different loading conditions according to forces applied to the crankshaft from the dynamic analysis.
5. Experimental stress 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.
6. Critical (i.e. failure) 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.

7. Geometry optimization resulted in 18% weight reduction of the forged steel crankshaft, which was achieved by changing the dimensions and geometry of the crank webs while maintaining dynamic balance of the crankshaft. This stage of optimization did not require any changes in the engine block or connecting rod.

8. As a result of geometry optimization , the weight of the crankshaft was reduced by 26%. Crankshaft geometry changes in this optimization stage required changing the main bearings in the engine according to the optimized diameters and using thrust bearings to reduce the increase of axial displacement of the crankshaft.
9. Adding fillet rolling was considered in the manufacturing process. Fillet rolling induces compressive residual stress in the fillet areas, which results in 165% increase in fatigue strength of the crankshaft and increases the life of the component significantly.

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