Impact of web and counterweight shape factors on crank shaft design for better strength and optimised geometry

G Mathan, J Daniel, P Vishnu and V Satyanarayana
Powertrain Division, Mahindra & Mahindra Ltd, Chennai, Tamilnadu, India
E-mail:g.mathan@mahindra.com

Abstract. Automotive industry is continuously focusing on developing weight efficient engines for better fuel economy without altering engine performance. To achieve a trade-off between performance and fuel economy, the design always demands downsizing of engine components with optimum geometry. Crankshaft is such an important component in deciding engine performance and overall weight. Torsional and bending stiffness of crankshaft plays a vital role in its structural integrity, particularly the Critical Cross Section (CCS) which connects main journal and crankpin. In the present study, the objective is to upgrade the crankshaft for higher torsional and bending stiffness and reduce weight without changing its performance. Three geometric shape factors of the crankshaft are identified and optimized in FEA and analyzed in AVL Excite® (1-D) simulation for its structural performance. Study shows the identification of shape factors and effect of their variation on torsional and bending stiffness of crankshaft. In addition, sensitivity analysis for various shape factors and their optimization has been done. The identified shape factors help designers to identify any scope to optimize the geometry of crankshaft and understand its role in structural strength. Using this methodology, specific regions defined by shape factors can be optimized for better strength and weight.

1. Introduction
An automotive Cranktrain assembly consists of crankshaft, connecting rod, pistons, piston pins and flywheel. Crankshaft transfers the combustion and inertial loads of cranktrain components to flywheel which in turn transfers it further to clutch and transmission. Diesel engines have high compression ratios, higher combustion pressures and hence high combustion loads. Crankshaft is one of the most stressed members in an engine and hence crankshaft optimization is rarely pursued in automotive industry. Due to increasing fuel efficiency requirements and impending CAFE (Combined Average Fleet Economy) regulations, weight reduction has become the main thrust area for OEMs. Approximately 10 percentage of the total engine weight is contributed by crankshaft and hence crankshaft can be considered as one of the heavier component in an engine assembly. Crankshaft is a rotating component which rotates at 1000-4000 RPM. It is very important to select possible weight reduction regions of crankshaft. A study shows drastic variation in crankshaft stiffness for same amount of material removal from different regions (1). Crankshaft contributes to 20-40% of frictional losses (FMEP) in an engine over different speeds. FMEP is directly proportional to contact area of running surfaces and weight of the component. Mass
reduction of rotating parts of engine provides advantage of lower power requirements during acceleration phase which measures drivability of vehicle (2).
In order to increase the power density of an engine, the requirement for higher cylinder pressures and hence higher torsional and bending stiffness of crankshaft becomes more relevant (3). Study shows about 10% increase in web width produces 15% increase in torsional strength whereas 10% increase in web thickness produces only 4% increase in torsion strength (4).
In this study, possibility of crankshaft weight reduction and stiffness optimization is analyzed. Three key regions are identified by respective shape factors and their effect on torsional and bending stiffness of crankshaft has been evaluated. Optimization of these shape factors have been done to achieve desired torsional and bending stiffness by DOE. 1-D simulation for the optimized crankshaft is done to confirm cranktrain design acceptance criteria. The present work consists of four major phases as shown as follow and as shown in figure 1

a.Identification of shape factors
b.Design of experiments and collection of data as per designs
c.Analysis of DOE results.
d.Optimization

2. Identification of Shape factors
Shape factors can be defined as dimensions of important features of a crankshaft. These factors should be selected in such a way that they don’t affect overall dimensions of the crankshaft. The shape factors were also selected in such a way that it doesn’t affect the critical cross section of crankshaft. Critical cross section (refer figure 2) is defined as the section between lowermost point of crankpin fillet and uppermost point of main journal fillet. This section comes in the area of pin overlap. Increase in pin
overlap results in increase in dimensions of critical cross section. Hence, three areas were selected which do not interfere with this critical cross section. They are as given below.

a. Web Top Offset Factor
b. Counterweight Profile Factor
c. Side Width Factor

Figure 2: Critical Cross-Section (CCS) of crank web

2.1 Web top face offset factor
The top face thickness is varying over its height as shown in figure 3. A control point was selected on the centre of the collar. The geometrical dimension X is defined as the horizontal distance between the control point and collar machined face. This X dimension is controlled by forging and manufacturing requirements (minimum material width required for forging). When adjusting the control point, another geometrical dimension Y also to be considered. This is the distance between control point and crankshaft rotating axis. Y is also constrained indirectly due to the profile of face. The web top face offset factor of (A) = X × Y is defined for this region. There are three levels of profile modification as shown in figure 3.

- Low level-red
- Medium level-Blue
- High level-Black

Figure 3: Web top face offset (A)
2.2 Counterweight profile factor
Counterweight profile was chosen as it is just under the critical cross section. This profile is controlled by two geometric dimensions D and R. The factor D is defined as the distance between crankpin centre and centre of profile radius. It is constrained due to minimum distance requirement between end of crankpin collar and start of profile. This distance was fixed as 7mm to take care of minimum stiffness requirement of crankshaft. The factor R is defined as the radius of cut. R is constrained due to minimum thickness requirement of counter weight width which is 10 mm. Counterweight profile factor (B) = D/R has been defined for this region. There are three levels of profile modification as shown in figure 4.

- Low level-Blue
- Medium level-Red
- High level-Green

![Figure 4: Counterweight profile (B)](image)

2.3 Side width factor
The sides of web have been defined by a geometric parameter called as Z. The dimension Z is defined as distance between the two outermost faces of crank web sides. Z has a constraint with respect to manufacturing as the distance between side face and main journal collar cannot be less than 2 mm. The side width factor (C) = Z/2 has been defined for this region. There are three levels of profile modification as shown in figure 5.

- Low-Red
- Medium-Blue
- High-Black
3. Stiffness calculation

Crankshaft torsional and bending stiffness are important in overall cranktrain performance. The crankshaft stiffness can be calculated analytically or numerically (FEA). In FEA, the stiffness of crankshaft is calculated by evaluating deformation under specified loading condition. Stiffness can be calculated analytically with length and diameter, hence all empirical relations generates equivalent length with major crankshaft dimensions. Some of the empirical relations are BICEAA provisional formula, Carter’s formula, Norman-Stinson’s formula, Timoshenko’s formula, Tuplin’s formula(5).

Study shows considerable difference in stiffness values calculated by FEA and applicable empirical formula. Small change in dimension causes large deviations between empirical and real values hence stiffness estimation by empirical equations is not reliable (6). Meshing influence study with hexa and tetra elements shows less than 1% variation and hence second order tetrahedron elements are used for the ease of meshing and with reasonable computational time (7).

Since the crankshaft shape is continuously varying across the length, the stiffness of the various regions has been evaluated individually. Each region stiffness values are used in the 1-D simulation later in the paper. For shape factor evaluation and optimization a representative region (Single Web) of the crankshaft has been selected. The stiffness evaluation as described in the present section is used in the next section (DOE). The crankshaft 3D model is split into different webs by using the following method. The crankshaft crankpins and main bearings are split at the centre. This gives us different webs for calculating stiffness. Figure 6 gives the methodologies of splitting crankshafts. These individual webs are evaluated for their stiffness using FEA.

Figure 5: Side width (C)

Figure 6: Splitting of crank shaft into individual webs
3.1 Torsional stiffness using moment

The 3D model of web is meshed using second order tetra elements. The nodes attached to the face of cut section are coupled to a single point at the centre of the section using rigid elements. Similarly the cut section at main bearing is also done. The centre of main bearing split section is also connected to the entire cut surface using rigid elements. The connected centre point of crankpin is constrained in all 6 degrees of freedom. A clockwise torsional moment of 1 N-mm is applied on the main bearing centre. The direction of moment application is parallel to crankshaft centre axis as shown in figure 7.

Figure 7: Boundary condition for torsional stiffness calculation by FEA

3.2 Bending stiffness using moment

The same finite element model which was used for torsional stiffness calculation is used for bending stiffness calculation. The connected centre point of crankpin is constrained in all 6 degrees of freedom. A bending moment of 1 N-mm is applied on the main bearing centre. The direction of moment application is perpendicular to crankshaft centre axis as shown in figure 8.

Figure 8: Boundary condition for bending stiffness calculation by FEA
4. Parametric study of shape factors (design of experiments)

For studying shape factors in crankshaft, the crankshaft of a 2.5Ltr 4 cylinder engine is selected. Design of experiments is a systematic method to determine the relationship between factors affecting a process and output of that process. Factorial designs allow for simultaneous study of the effects that several factors may have on output. While designing experiments, varying the levels of the factors simultaneously rather than One Factor at a Time (OFAT) is efficient in terms of time and cost. In full factorial experiment, responses are measured for all combinations of the experimental factor levels. These combinations represent conditions at which responses will be measured. Each experiment condition is called as “Run”, response measurement as “Observation” and entire set of runs is called as “Design” (8).

Number of runs are given by the following formula:
\[
\text{Number of runs} = \text{Level}^{\text{Factors}}
\] (1)

4.1 defining factors
In this experiment input parameters or factors of interest are as designated in Table 1.
- Web Top Face Offset (A)
- Counterweight Profile (B)
- Side Width (C)

4.2 defining responses
Crankshaft rigidity can be indicated with Torsional and Bending stiffness. These two responses are captured for each set of input conditions and evaluated.

4.3 DOE
Minitab® [8] is used to design experiments by defining factors and expected response parameters. The sequence and configuration of experiments is as follows in Table 2.

Table 1: Crankshaft shape factors

| Factors            | Symbol | Level 1 | Level 2 | Level 3 |
|--------------------|--------|---------|---------|---------|
| Web Top Face Offset| A      | 1       | 2       | 3       |
| Counterweight Profile| B  | 1       | 2       | 3       |
| Side Width         | C      | 1       | 2       | 3       |
Table 2: Design of Experiments

| Iteration | A  | B  | C  | Iteration | A  | B  | C  |
|-----------|----|----|----|-----------|----|----|----|
| 1         | 1  | 1  | 2  | 15        | 1  | 2  | 3  |
| 2         | 3  | 1  | 3  | 16        | 2  | 2  | 3  |
| 3         | 3  | 3  | 1  | 17        | 3  | 2  | 2  |
| 4         | 3  | 1  | 1  | 18        | 2  | 2  | 1  |
| 5         | 1  | 3  | 1  | 19        | 2  | 1  | 1  |
| 6         | 3  | 2  | 3  | 20        | 2  | 3  | 3  |
| 7         | 2  | 2  | 2  | 21        | 1  | 1  | 3  |
| 8         | 3  | 3  | 2  | 22        | 3  | 2  | 1  |
| 9         | 2  | 3  | 2  | 23        | 1  | 2  | 1  |
| 10        | 3  | 1  | 2  | 24        | 2  | 1  | 3  |
| 11        | 3  | 3  | 3  | 25        | 2  | 3  | 1  |
| 12        | 1  | 3  | 2  | 26        | 1  | 1  | 1  |
| 13        | 1  | 2  | 2  | 27        | 2  | 1  | 2  |
| 14        | 1  | 3  | 3  |           |     |    |    |

4.4 Regression analysis

Regression is widely used method in statistics to discover the influence of more than one input variable on output response [9]. Linear multiple regression model is as shown in the equation 2
\[
y = b_0 + b_1x_1 + b_2x_2 + \ldots \tag{2}
\]

More detailed model can be defined according to predicted response and required accuracy. Following equation shows second order model with interaction effect
\[
y = b_0 + b_1x_1 + b_2x_2 + b_3x_1^2 + b_4x_2^2 \ldots \tag{3}
\]

Using Minitab® regression analysis, torsional and bending stiffness can be expressed as,

Torsional Stiffness = f\{A, C, A C, B\} \tag{4}

Bending Stiffness = f\{A^2, C^2, B^2\} \tag{5}

Equations 4 and 5 indicates quadratic relation between torsional/bending stiffness and shape factors (Table 3).

Table 3: Quality of regression model

| Equation       | $R^2$   | $R^2_{adjused}$ | $R^2_{predicted}$ | Model   |
|----------------|---------|-----------------|-------------------|---------|
| Torsional      | 99%     | 98.8%           | 98.51%            | Quadratic |
| Bending        | 94.6%   | 93.9%           | 92.77%            | Quadratic |

Correlation coefficient $R^2$ above 90% shows that it is stable model with reliable predictability indicated by high predictability values $R^2_{predicted}$ is above 90%.

Residual plots for above two regression models are shown in figure 9 and 10 and indicates goodness of model fit.

Normal probability plot: Points in this plot form approximate straight line hence residuals are normally distributed (refer figure 9 and 10).

Residuals versus fits: Random pattern of residuals on both sides of zero and hence no recognizable pattern (refer figure 9 and 10).

Residuals versus order: Plot of all residuals in an order that data was collected and used to find non-random error (refer figure 9 and 10).

Histogram of residuals: Indicates normally distributed residuals (refer figure 9 and 10).
4.5 Interpretation of doe results

Significant and insignificant factors can be identified by plotting means of response simulated in experiments against each level of factors. These plots helps us to establish the trend in direction of variation of response for unit change in input factors.

4.5.1 Torsional stiffness. Main effects plot for torsional stiffness shows that web top face offset (A) and side width (C) has major effect on torsional stiffness and relation is quadratic in nature as shown in figure 11. Both these factors has “Higher the better” relation with torsional stiffness. Higher the factor means more material and increase in stiffness. Counterweight profile (B) is not very sensitive to torsional stiffness of the crankweb. Variation in shape factor ‘B’ is not altering CCS and hence effect on torsional stiffness is not that significant.
4.5.2 Bending stiffness. Main effects plot for bending stiffness shows that web top face offset (A) and side width (C) has major effect on bending stiffness. Both these factors has “Higher the better” relation with bending stiffness and this relation is quadratic as shown in figure 12. Higher the factor means more material and increase in stiffness. Counterweight profile (B) is not very sensitive to bending stiffness of the crankweb. Variation in shape factor ‘B’ is not altering CCS and hence effect on bending stiffness is not that significant.

5. Optimization of shape factors
Statistical optimization of shape factors is done through “OptQuest” (Excel based tool) [11]. Shape factors are defined as ‘Decision Variables’ which can be varied in the defined range. Torsional and bending stiffness of crankshaft are defined as ‘Forecast Variables’ (Output variables) and minimum values of stiffness are kept as ‘Constraints’. Solution gives desired values of shape factors to satisfy stiffness constraints. Slight variation of these values are done to meet balancing requirement and manufacturing constraints.
Crankshaft is designed with finalized values of shape factors and further used for 1-D simulation through AVL Excite®.
6. Analysis of strength and torsional vibrational performance

Strength and torsional vibration of the crankshaft cannot be determined without the whole Cranktrain assembly. A specialized commercial software called as AVL EXCITE® [10] is used to determine these parameters. 1-D simulation of the optimized crankshaft is done to confirm cranktrain design acceptance criteria.

Excite model of Cranktrain is a condensed representation of actual physical crank train system [10]. The geometry of various parts and their physical properties such as Mass moment of inertia and mass are given as inputs in this model. The various Cranktrain components such as piston, piston pin, connecting rod, flywheel, and damper are defined in terms of their mass moments of inertia and geometry.

The crankshaft is reduced to a simplified model of masses which are connected by springs with stiffness (spring-mass system). All the components are finally connected and loads on the Cranktrain, i.e., peak firing pressure in combustion chamber is applied to the system. Refer figure 13 for schematic representation of excite model.

![Figure 13: Cranktrain model in AVL Excite®](image)

Above mentioned Multi-Body Dynamic (MBD) model is solved and following standard results as shown in figure 14-18 are obtained. It is observed that all these results are within acceptable limits. It shows that, crankshaft stiffness achieved by optimization of shape factors is sufficient to pass standard Cranktrain acceptance criteria.
Figure 14: Torsional vibration amplitude at hub (degrees)

Figure 15: Speed irregularity at flywheel end

Figure 16: Torsional stresses at crankpin (MPa)

Figure 17: Crank pin fillet safety factor
7. Summary

The shape factors governing the performance of crankshaft web have been identified. The methodology to optimize the crankshaft weight has been established. The following conclusions have been made from this work.

1. Top face offset and side width have major effect on torsional and bending stiffness.
2. Counterweight profile has less significant effect on torsional and bending stiffness
3. Crankshaft designed with optimized shape factors satisfies all design acceptance criteria.
4. This methodology can be implemented in early design phase to get weight and stiffness optimized crankshaft design.

8. References

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