Method for assessing the adequacy of a crankshaft strain state model

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Abstract. Using the Finite Element Method (FEM) in the SolidWorks software environment, the strain crankshaft state is modelled. The assessment of the adequacy of the model by experimental crankshaft in a running engine is complex and is possible for a small number of control points. The method shown proposes to replace the variable crankshaft strains in motion by examining a static strain state of the crankshaft. The results obtained show a high degree of adequacy of the model. The differences can be minimised by specifying the physical properties of the material used in the simulation, taking into account the elasticity of the supports.

1. Introduction

In the design phase of internal combustion engines, models are always used to determine various phenomena and processes which occur in their operation. The study of stress and strain state of the engine's main elements is inconceivable without the application of Finite Element Method (FEM). It is applied in various software environments, one of which is SolidWorks [1]. In this software environment, a model of diesel engine crankshaft has been created [2]. The results obtained by the model give an opportunity to assess the impact of small changes in the crankshaft shape on its strength and its stress and strain state.

The created model adequacy is assessed experimentally. This assessment in needed to prove the relevance of the results obtained through the model. The adequacy is usually proven by measuring the stress of prepared crankshaft placed under loading conditions close to the real ones. The complexity of this task results in compromises and large inaccuracies of the experiment and therefore the safety of the results obtained in the measurement is small. On the other hand, the accuracy of mechanical characteristics laid down in the model and boundary loading and attachment conditions are crucial to the accuracy of the results obtained from the model studies. In fact, it is more important to set the model and its parameters so that it corresponds to reality. It is not necessarily to do this by testing a crankshaft under real operating conditions.

The aim of the presented work is to test a method for assessing and specifying the crankshaft model by static shaft loading and measuring deformations in a sufficient number of points. The degree of coincidence of the measured deformations with those obtained in the modelling is sufficient criterion for adequacy of the developed crankshaft model.
2. Experimental test and model
Crankshaft mounted on a lathe is used in the presented method. The shaft front end is fixed to the lathe chuck and the rear end is fixed to the lathe with the help of alignment device. Thus, the shaft can rotate but can not change its axis of rotation, figure 1. A lever is attached to the crankshaft rear end by means of transition flange.

![Figure 1. Fastening of the crankshaft to a lathe.](image)

At the end of the web, different weights can be attached. Sufficiently rigid support is placed under crank pin 1 (which is the closest to shaft front end) so that the shaft can not be turned over, figure 2. The load applied to the lever, combined with the support under crank pin, creates torsion of the crank pin crankshaft. The shaft deformations and corresponding displacements of certain points on its surface can be measured with the help of dial gauge.

![Figure 2. Scheme of fastening and load](image)

Figure 3 shows the points of measurement. These are the central areas on the upper surface of all crank pins (P.2, P.5, P.7, P.8), two of the counterweights (P.4, P.9) and the main crank pins (P.3, P.6, P10, P.11). Measurement is also performed on the flange at the crankshaft rear end on which the web is attached (P.1). The accuracy of displacement measurement is 0.001mm.
Three-dimensional model is created for the actual crankshaft and additional elements in the SolidWorks environment. All details of the shaft shape, flange, web and support are reflected. Figure 4 shows the connection between the crankshaft rear end and web through the transition flange. The three-dimensional image of the model copies precisely the real elements. Figure 5 shows the crankshaft and type of support under the first crank pin.

Figure 3. Top view - points of measurement.

Figure 4. Rear end crankshaft, flange and lever

Figure 5. Support under the first crank pin

The boundary fastening conditions are as follows:
- at the crankshaft front end bearing support and axis fixing are implemented, figure 6;
- the support under the first crank pin is permanently fixed in all directions; it in turn restricts the shaft rotation, figure 6;
- at the crankshaft rear end bearing support is provided in the web opening - contact with the lathe alignment device is made there, figure 7;
- loading is set on a small platform at the web end, figure 7.

The initial version of the model with absolutely rigid supports is not very reliable. Therefore, after measuring the deformations in the supports and calculating the supporting reactions, the support stiffness was determined and set in the model, table 1. Under these fastening conditions, the tests in SolidWorks environment have been performed, using elastic supports.
3. Experimental results

Deformations in the eleven points shown are measured consequently three times and the average values of the three measurements are accepted. The system was initially loaded with approximately 40N to remove the clearance. The values at this loading are accepted as initial ones and the instrumentation is reset. The load is then increased to approximately 200N to reach the maximum load of 824N and is reduced by the same step to the initial level.

| Load (N) | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 | Point 6 | Point 7 | Point 8 | Point 9 | Point 10 | Point 11 |
|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 392      | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       |
| 235,4    | 0.0033  | -0.0257 | 0.0800  | 0.0557  | 0.4180  | 0.1200  | 0.401   | 0.382   | 0.385   | 0.3893  | -0.1493 | -0.3167 |
| 341,6    | 0.0207  | -0.0330 | 0.1783  | 0.1150  | 0.7750  | 0.2333  | 0.745   | 0.724   | 0.729   | 0.7327  | -0.2680 | -0.5400 |
| 627,8    | 0.0433  | -0.0377 | 0.2210  | 0.1683  | 0.9807  | 0.3067  | 0.933   | 0.922   | 0.927   | 0.9273  | -0.3247 | -0.7300 |
| 824      | 0.0567  | -0.0427 | 0.2727  | 0.2050  | 1.1767  | 0.3667  | 1.115   | 1.093   | 1.100   | 1.1027  | -0.3850 | -0.8883 |
| 627,8    | 0.0667  | -0.0433 | 0.2817  | 0.2133  | 1.0357  | 0.3417  | 0.972   | 0.951   | 0.957   | 0.9600  | -0.3253 | -0.8417 |
| 341,6    | 0.0623  | -0.0433 | 0.2467  | 0.2067  | 0.8497  | 0.2867  | 0.794   | 0.781   | 0.785   | 0.7867  | -0.2637 | -0.6800 |
| 235,4    | 0.0483  | -0.0400 | 0.1377  | 0.1167  | 0.4777  | 0.1617  | 0.448   | 0.431   | 0.438   | 0.4390  | -0.0520 | -0.4117 |
| 392      | 0.0117  | -0.0013 | 0.0000  | -0.0067 | 0.0047  | 0.0133  | 0.016   | -0.007  | 0.000   | 0.0030  | 0.0017  | -0.0383 |

Table 2 shows the average values of the measured deformations at all points. For example, the values of the three measurements are shown only in point 7. For illustration, figure 8 shows the changes in the deformations of the main journals at the change of loading.
Figure 8. Measured strains of the main journals (MJ) of the crankshaft.

Figure 9. Measured strains of the crank pins 2 and 3 (CP) and counterweight 4 (CW4) of the crankshaft.

Figure 10. Measured strains of the crank pins 1 and 4 (CP) and counterweight 2 (CW2) of the crankshaft.
Figure 9 shows the deformations of points from counterweight 4 and crank pins 2 and 3 that move in the direction chosen as positive. Figure 10 shows the negative displacements of the points from counterweight 2 and crank pins 1 and 4.

4. Adequacy of the model
The same loads as those used in the real experiment are applied to the crankshaft model described above. Two tests were made - test with absolutely rigid supports at points 1, 2 and 3 and test with the same supports which elasticity is defined in table 1. Table 3 shows the results of the numerical studies of the displacements of all points with rigid and elastic supports and comparison with the experimental results. The values shown are in (mm).

| Type of study         | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 | Point 6 | Point 7 | Point 8 | Point 9 | Point 10 | Point 11 |
|-----------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|----------|----------|
| rigid supports - rs    | 0,0271  | -0,0141 | 0,1063  | 0,3479  | 0,5684  | 0,2554  | 0,5644  | -0,1585 | -0,0513 | 0,2707   | 0,2839   |
| elastic supports - es | 0,0580  | -0,0425 | 0,2819  | 0,3697  | 0,7923  | 0,3169  | 0,7619  | -0,2649 | -0,1870 | 0,3556   | 0,3315   |
| experimental - e      | 0,0567  | -0,0427 | 0,2727  | 0,2050  | 1,1767  | 0,3667  | 1,1027  | -0,3850 | -0,8883 | 0,5467   | 0,4977   |
| \( \Delta = e - es \) (mm) | -0,0013 | -0,0002 | -0,0092 | -0,1647 | 0,3844  | 0,0498  | 0,3408  | -0,1201 | -0,7013 | 0,1911   | 0,1662   |
| \( \Delta\% = \frac{100 \Delta}{e} \) (%) | -2,3    | 0,4     | -3,4    | -80,3   | 32,7    | 13,6    | 30,9    | 31,2    | 78,9    | 35,0     | 33,4     |

The first row in table 3 shows the results of the deformations obtained through the model in SolidWorks environment with absolutely rigid supports in points 1, 2 and 3. The second row shows the results in the use of elastic supports with a stiffness set out in table 1. The next row shows the experimental results. Below are the differences between the experimental results and elastic support study, with the absolute values of the differences and their relative value in percentage being shown.

The deformation direction of the model and that of the real crankshaft coincide in all control points. Larger deviations at points 4 and 9 are noticeable. These are counterweight points. They are located at the greatest distance from the shaft axis and the probability of a measurement error is greatest. In addition, they fall outside of the field lines through the crankshaft under this loading scheme and are not important to the overall strain state of the shaft. The deviations of the support points are negligible. The deviations of the remaining points are within the limits and can be reduced in case of any change in the elastic characteristics of the material set in the crankshaft model.

One of the objectives of the proposed method is to adjust the model parameters so as to achieve maximum identity with the real crankshaft. Then crankshaft studies can be made with the specified parameters of the model in the set operating and loading conditions.

5. Conclusion
The proposed method of specifying the crankshaft model and assessing its adequacy is applicable to crankshafts of automobile engines and to modelling in SolidWorks environment.

The approach in the proposed method is universal and it can be applied to models created with other software that uses the Finite Element Method.

Setting the numerical model and specifying the material characteristics set therein is perfectly possible with high precision through the proposed method.

6. References
[1] Karavasilev O, Kozhuharov M, Dimitrov N, Grigorov B and Mitrev R 2012 *SolidWorks-Basic modeling and drawings* (Sofia: TechnoLogica) p 600.
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