IOP Conf. Series: Materials Science and Engineering **393** (2018) 012069 doi:10.1088/1757-899X/393/1/012069

A computer program for IC engine crankshaft main bearings wear diagrams

N M Nikolić[1,2], J Ž Dorić[1] and B M Stojić[1]

[1]University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia

E-mail: nebnik@uns.ac.rs

Abstract. IC engine crankshaft bearings are amongst the most loaded parts of the engine. Forces, acting on crankshaft bearings are changed very intensively during the engine operating cycle. Therefore, it would be very useful to have a visual representation of the bearings wear. For that purpose, a computer program has been developed to generate theoretical wear diagrams for all the crankshaft bearings of the engine. Theoretical wear diagrams provide a picture of the bearing material wear distribution resulting from the bearing load. The bearing load calculations used in the program are based on a statically indeterminate method. The description of the program, followed by some illustrations of its application, has been given in the paper.

1. Introduction

In the majority of internal combustion (IC) engines, forces between crankshaft journals and bearings have high magnitudes, and as such, are considered to be the most important factor affecting the wear of the elements in contact. It is very difficult to understand and describe the wear phenomenon, especially if all the possible influence parameters such as geometry and temperature of contact, physical and chemical properties of the contacting materials etc. are taken into account.

Many diverse research works have been presented recently showing the great significance of wear in mechanical systems [1-5]. In [1-5], the authors developed the models to compute the wear depth in order to predict wear after a certain period of time or number of cycles. However, as far as the main bearings of an internal combustion engine are concerned, it is not of much interest to predict the wear depth, but rather to determine the most jeopardized bearings of an IC engine and to estimate the most critical areas on the bearing surface in terms of wear. For that reason, Nikolic et al. [6] proposed an algorithm for constructing a theoretical wear diagram, by the use of which one can determine the most jeopardized crankshaft bearings and estimate the most critical zones on their surface.

The theoretical wear diagram has the form of a worn out bearing profile and it is therefore called a theoretical wear diagram [7]. It is constructed with the assumption that a contact between the journal and the bearing is unlubricated. The assumption is related to the theoretical case, when the journal and the bearing are in a direct contact, but it can also be related to critical operation regimes with sparse lubrication or no lubrication of IC engine bearings.

During the research described in reference [6], a computer program has been developed, that is able to automatically generate wear diagrams for the appropriate IC engine input data. The computer program is given the name after the final results that it produce - "Wear diagrams". It is the aim of this paper to describe what the computer program is capable of and how it operates.

The paper is structured as follows. Basic principles of crankshaft bearings load and wear determination and final equations used in the development of the "Wear diagrams" computer program are given in Section 2. Section 3 describes the user interface of the program in detail. Some results of the program, obtained by its application on a five-cylinder diesel engine, are presented in Section 4. Section 5 contains conclusions.

2. Determination of wear based on crankshaft bearings load

The computer program "Wear diagrams" is an upgrade and improvement of the computer program "Polar diagrams" described in reference [8]. It is based on the procedure for constructing a theoretical wear diagram of IC engine crankshaft main bearings shown in reference [6]. Therefore, an interested reader can there find a detailed description of the algorithm developed as well as complete mathematical model with the appropriate equations derived.

In the model, crankshaft is treated as a statically indeterminate beam and the load distribution on the contact surface between a journal and a bearing is assumed to be elliptic.

Figure 1 shows the schematic view of an in-line engine crankshaft with (n+1) main bearings with the forces acting on them. Two coordinate systems are also shown in Figure 1, one of which is stationary (OXY) and the other one (OX1Y1) rotates together with the crankshaft with the angular velocity ω. The position of the coordinate system OX1Y1 with respect to the coordinate system OXY is defined by the crankshaft angle φ. It should be noted that all the forces depicted in Figure 1 depend on this angle.

Each crank force Fc_i (i=1,...,n) that originates from the crank i is distributed to all the bearings, not only to the adjacent ones. The forces Fc_i can be calculated in a common way taking into account gas forces and inertia forces that dominate over other forces in IC engines. The gas forces can be measured or modelled by using some of the known methods and the inertia forces can be easily determined by using Newton's second law of motion assuming that the crankshaft rotates with a constant angular velocity. Therefore, the forces Fc_i can be considered as known.

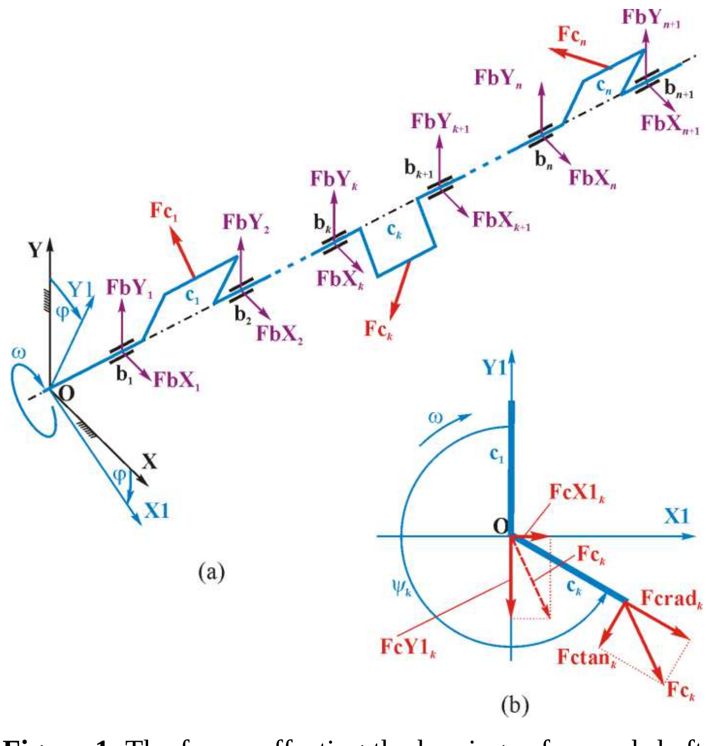

Figure 1. The forces affecting the bearings of a crankshaft: (a) an isometric view; (b) a side view.

In [6] it is shown that each force $Fb_j(\varphi)$ acting on the main bearing b_j, (j=1,...,n+1) can be expressed by its projections on X and Y axes:

$$FbX_j(\varphi) = FbX1_j(\varphi)\cdot\cos\varphi + FbY1_j(\varphi)\cdot\sin\varphi$$
$$FbY_j(\varphi) = -FbX1_j(\varphi)\cdot\sin\varphi + FbY1_j(\varphi)\cdot\cos\varphi \quad (1)$$

where $FbX1_j$ and $FbY1_j$ are the projections of the force Fb_j onto the coordinate system OX1Y1:

$$FbX1_j(\varphi) = \sum_{i=1}^{n}\left(-\rho_{i,j}\cdot Fcrad_i(\varphi_i)\cdot\sin\psi_i + \rho_{i,j}\cdot Fctan_i(\varphi_i)\cdot\cos\psi_i\right)$$
$$FbY1_j(\varphi) = \sum_{i=1}^{n}\left(\rho_{i,j}\cdot Fcrad_i(\varphi_i)\cdot\cos\psi_i + \rho_{i,j}\cdot Fctan_i(\varphi_i)\cdot\sin\psi_i\right) \quad (2)$$

$Fcrad_i$ and $Fctan_i$ are radial and tangential components of the crank force, $\rho_{i,j}$ are the influence coefficients [6], ψ_k is the counterclockwise angle between cranks c_1 and c_k (Figure 1b) and φ_i is the angle that indicates the position of crank c_i during the appropriate engine cycle. Considering that engine cycle in cylinder i advances by angle θ_i relative to the engine cycle in cylinder 1, the following relationship between angles φ_i and φ is valid - $\varphi_i = \varphi + \theta_i$. The force Fb defined by equation (1) is transferred from the main journal to the main bearing, causing the contact between these two elements to be established, as shown in Figure 2. Pressure distribution within the contact area is assumed to be elliptic [6],

$$p(\beta) = p_{max}\cdot\left(1-\left(\frac{\beta}{\beta c}\right)^2\right)^{1/2} \quad (3)$$

where p_{max} is maximum pressure in the contact area and depends on the load, the contact geometry and bearing and journal materials properties [6]

$$p_{max} = 0.55\cdot\frac{Fb}{L\cdot Rb}\cdot\left(\frac{1}{\beta c}+0.35\right) \quad (4)$$

Assuming that the wear of the bearing is proportional to the pressure $p(\beta)$ and gradually increasing parameter φ to the end of the engine cycle, it is possible to calculate non-dimensional cumulative conditional wear depth as it is shown in [6]. Based on that calculation a computer program "Wear diagrams" has been developed.

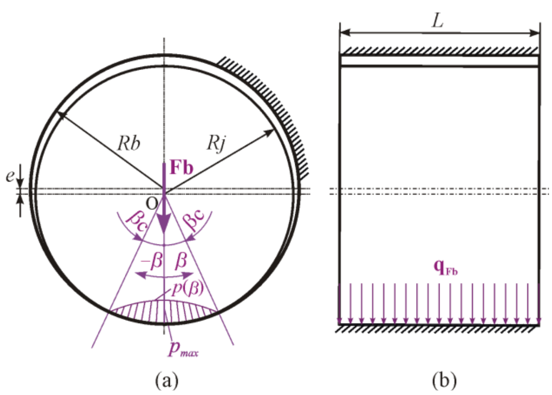

Figure 2. Geometry of the journal-bearing contact: (a) a front view; (b) a side view.

3. Description of the program

The computer program "Wear diagrams" is written by using Mathworks Matlab software. The user interface of the program is shown in Figure 3 and is divided into seven segments that are enumerated accordingly, indicating the order of data input.

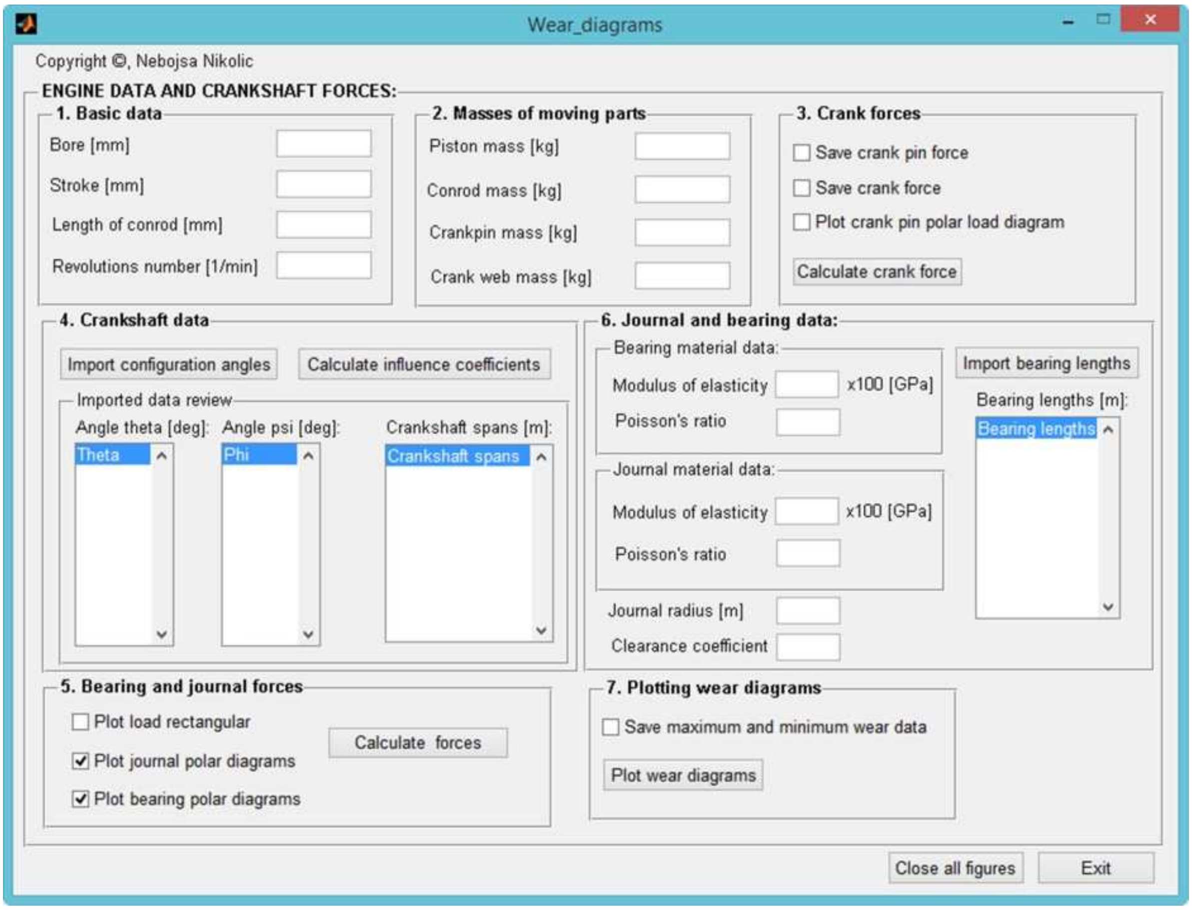

Figure 3. The user interface of the program "Wear diagrams".

The segment 1, with an example basic engine data entered into the form, is shown in Figure 4. The data involve cylinder bore, piston stroke, length of the connecting rod and engine speed.

Then, the masses necessary to calculate inertial forces of the crank gear should be entered and it is done in segment 2. These are the masses of the piston, connecting rod, crank pin and crank web, as it can be seen for the example data, shown in Figure 5.

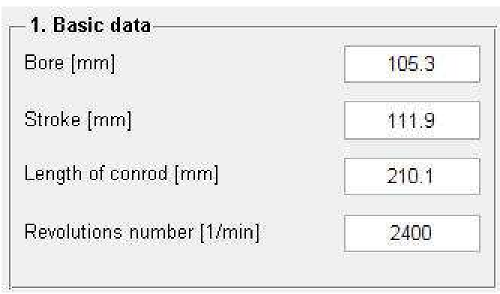

Figure 4. Input of basic engine data.

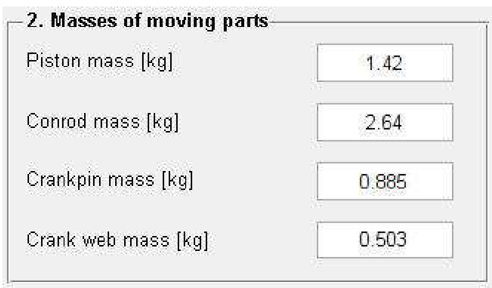

Figure 5. Input of crank gear elements masses.

To calculate crank force, cylinder pressure values throughout the whole engine cycle are needed. These values are imported from an excel file to the “Wear diagrams” program. By pressing the button “Calculate crank force” in segment 3 of the program (Figure 6), a dialog box is opened so the user can choose the appropriate excel file containing the cylinder pressure values. Figure 6 also shows additional options by which the user can choose whether to save crank force and crank pin force values to excel files or not and also whether to plot crank pin polar load diagram or not. After succesful crank force calculation, a message box apears (Figure 7) and directs the user to the next step i.e. to enter the crankshaft data.

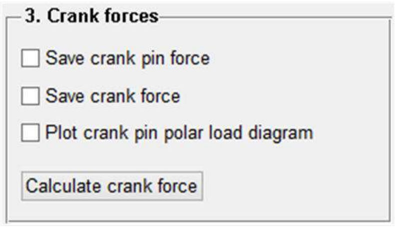

Figure 6. User interface segment for calculating crank force.

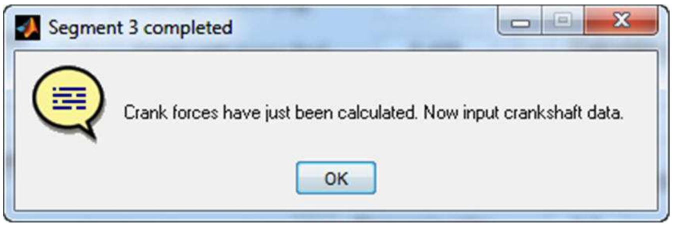

Figure 7. “Segment 3 completed” message box.

Crankshaft data involve so called configuration angles and crankshaft spans. Engine cycle phase angles (theta - θ) and spatial crank angles (psi - ψ) are here named configuration angles. Phase angles depend on the engine firing order and spatial crank angles depend on spatial configuration of the crankshaft. All the mentioned crankshaft data are imported from excel files and this is done in segment 4 of the program (Figure 8). By pressing the button “Import configuration angles”, a dialog box opens, offering the user to select an excel file containing angles theta and psi. After the excel file is selected, the imported data appear in appropriate listboxes as shown in Figure 8 for a five-cylinder in-line engine. Further, by pressing the button “Calculate influence coefficients”, another dialog box opens, where the user can choose an excel file with the crankshaft spans data. The rightmost listbox in Figure 8 is populated with the data from the chosen excel file and influence coefficients are calculated thereafter. Then, a message box appears, informing the user that the segment 4 is completed and suggesting the user what to do next.

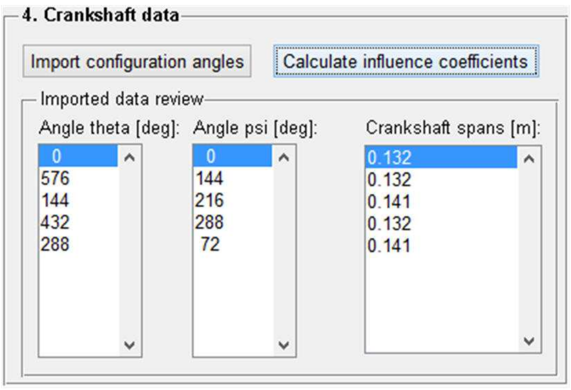

Figure 8. Input of crankshaft data and influence coefficients calculation.

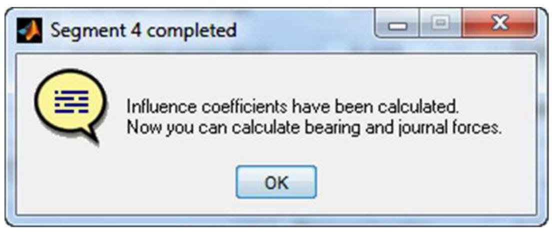

Figure 9. “Segment 4 completed” message box.

With the crank force and influence coefficients known, it is possible to calculate journal and bearing forces. This is done by simply pressing the button “Calculate forces” in segment 5, shown in Figure 10. After the calculation has been completed, appropriate diagrams are plotted for each crankshaft main journal and/or bearing, depending on the checkboxes checked in segment 5.

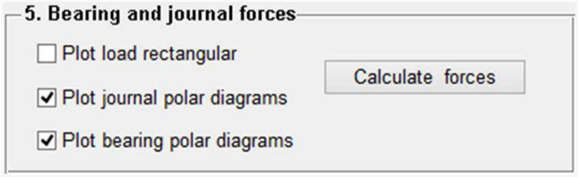

Figure 10. User interface segment for calculating bearing and journal forces.

The final data input, before plotting the wear diagrams of the crankshaft main bearings, is performed in segment 6 (Figure 11) of the “Wear diagram” program. As Figure 11 shows, the data related to journal and bearing materials and geometry are needed. The user should enter modulus of elasticity and Poisson’s ratio of the journal and bearing materials as well as journal radius and clearance coefficient. At the end, the length of each bearing is necessary for plotting the wear diagrams. These data are contained in an excel file and are imported to the program by using a dialog box which is opened after pressing the button “Import bearing lengths”. The imported data appear in appropriate listbox as shown in Figure 11.

After segment 6 has been completed, all the necessary data are prepared for plotting the wear diagrams for each main bearing. This is done by pressing the button “Plot wear diagrams” in segment 7, shown in Figure 12. In segment 7, there is also an additional option represented by checkbox “Save maximum and minimum wear data”. By checking this checkbox, the user can save specific data in an excel file. These data involve maximum and minimum intensity of wear and also their locations on the bearing circumference for each bearing. Examples of the wear diagrams and the associated specific data are shown in the next section of the paper.

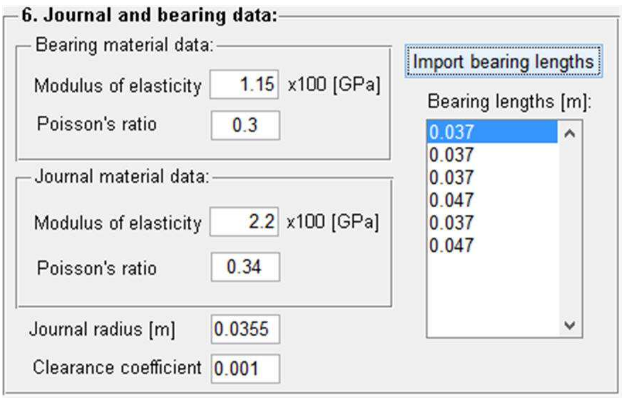

Figure 11. Input of journal and bearing data.

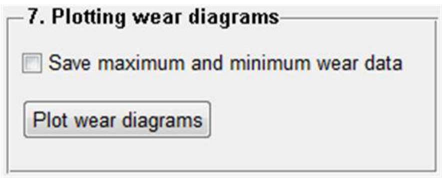

Figure 12. User interface segment for plotting wear diagrams.

4. Illustration of the program application

To illustrate application of the program developed, a five-cylinder in-line diesel engine is taken as an example. Some of the basic data used are already shown in Figures 4, 5, 8 and 11.

Figures 13-18 show the wear diagrams for all the engine bearings. As it can be seen, bearing worn-out surface is symbolically represented by a blue-coloured hatched area. Thus, the user can conclude which bearing is mostly jeopardized and where on the bearing surface the wear is the most serious. Next to each wear diagram, one can see the maximum and minimum values for ΔR, that represent maximum and minimum wear intensity. Further, there are also α(ΔR) values written at the diagrams, precisely showing the most and the least loaded locations on the bearing surface. Looking at Figures 13-18, it can be concluded that bearing 3 is exposed to the most intense wear, and bearing 6 to the least intense wear. The wear diagrams offer more useful information. For example, taking the closer look at Figure 15, one can conclude that minimum wear intensity of bearing 3 amounts 651 units and appears at angle α=221°, measured from the positive X-axis. Further, maximum wear of 1262 units appears at angle α=14°, measured also from the positive X-axis. These data are available for all the bearings in their wear diagrams.

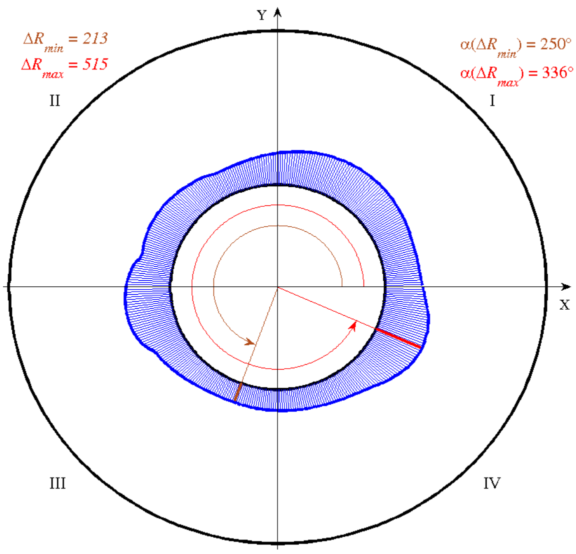

Figure 13. Wear diagram of bearing 1.

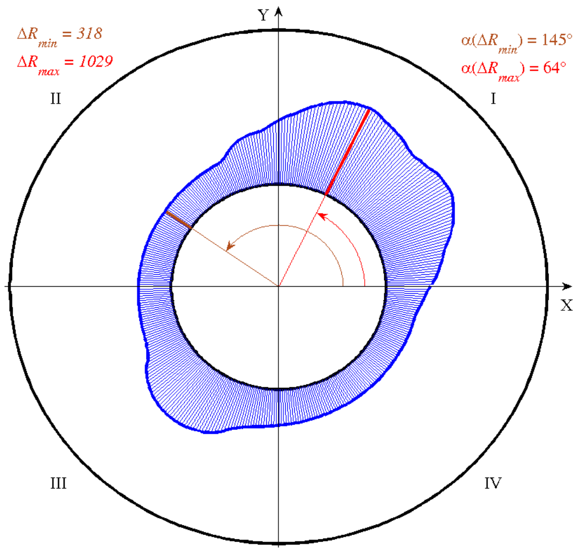

Figure 14. Wear diagram of bearing 2.

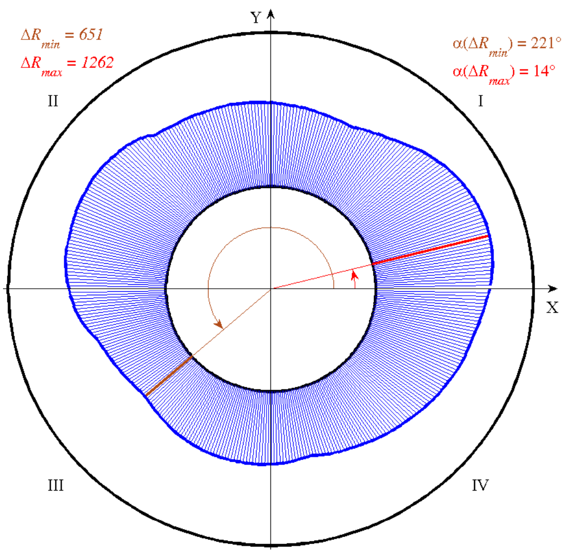

Figure 15. Wear diagram of bearing 3.

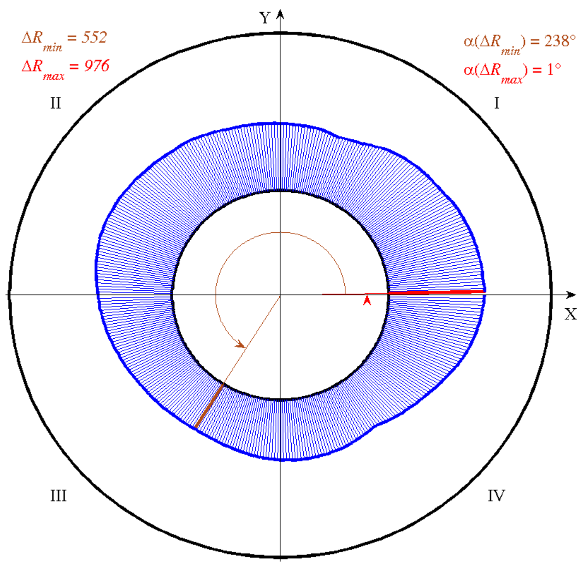

Figure 16. Wear diagram of bearing 4.

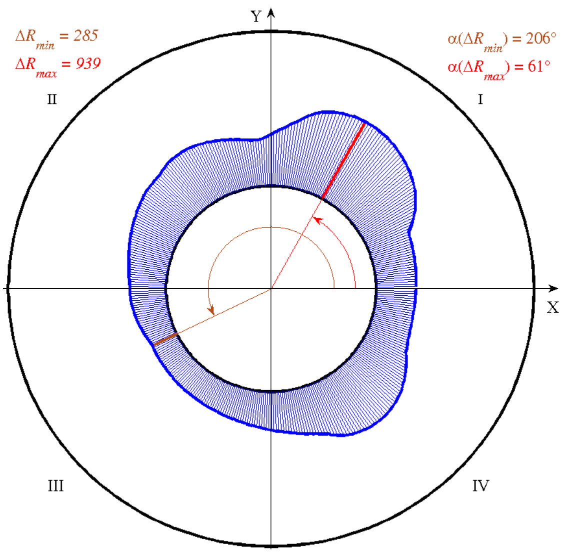

Figure 17. Wear diagram of bearing 5.

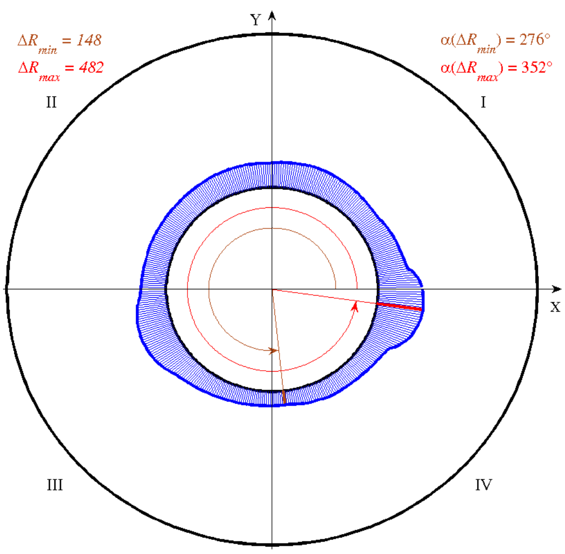

Figure 18. Wear diagram of bearing 6.

5. Conclusion

An interactive computer program for plotting wear diagrams of IC engine crankshaft main bearings has been developed and described in this paper. Wear diagrams enable one to compare different bearings in wear intensity and to determine the regions on the bearing surface that are exposed to heavier wear than others. A part of the program benefits has been illustrated by the results obtaind after the program had been applied to a five cylinder in-line engine.

Acknowledgments

The authors acknowledge support received from the Ministry of Education, Science and Technological Development, Republic of Serbia (Project No. TR31046, under the name "Improvement of the quality of tractors and mobile systems with the aim of increasing competitiveness and preserving soil and environment").

References

[1] Meng H C and Ludema K C 1995 Wear Models and Predictive Equations: Their Form and Content, *Wear* **181-183**(2) 443-457
[2] Flores P 2009 Modeling and Simulation of Wear in Revolute Clearance Joints in Multibody Systems, *Mechanism and Machine Theory* **44** 1211-1222
[3] Mukras S 2010 Comparison Between Elastic Foundation and Contact Force Models in Wear Analysis of Planar Multibody System, *ASME Journal of Tribology* **132** 31604-1–031604-11
[4] Mukras S, Kim N H, Mauntler N A, Schmitz T L and Sawyer W G 2010 Analysis of Planar Multibody Systems with Revolute Joint Wear, *Wear* **268** 634-652
[5] Su Y, Chen W, Tong Y and Xie Y 2010 Wear Prediction of Clearance Joint by Integrating Multibody Kinematics with Finite-Element Method, *Journal of Engineering Tribology* **224** 815-823
[6] Nikolic N, Torovic T and Antonic Z 2012 A Procedure for Constructing a Theoretical Wear Diagram of IC Engine Crankshaft Main Bearings, *Mechanism and Machine Theory* **58** 120-136
[7] Lukanin V N and Shatrov M G 2007 *Internal Combustion Engines, Dynamics and Design*, Vishaya shkola
[8] Nikolić N, Dorić J and Jocanović M 2016 *A Computer Program for the Visualization of IC Engine Crankshaft Main Bearings Load*, 9th International Symposium on Machine and Industrial Design in Mechanical Engineering KOD, Balatonfured, Hungary, June 9-12, pp 89-92