# ANALYSIS OF DYNAMIC CHARACTERISTICS OF ROLLING BEARINGS IN ROTOR SUPPORTS

N. KIKOT
S. DEGTIAREV
M. LEONTIEV
E. SNETKOVA

*The article considers the methodology of analysis of deformed and force state of angular contact bearings as a part of rotor systems. Developed on its basis model and algorithms are included into the program system DYNAMICS R4. The bearing model has 5 degrees of freedom, takes into account its geometry, the number of rolling elements, their inertia and clearance. Algorithms of the program system allow obtaining the position of outer and inner bearing races for every regime with given rotating speed, radial and axial forces, temperature and taking into consideration the rotor weight. Using the program, it is also possible to determine contact angles for every rolling element, all loads acting along 5 degrees of freedom. This information is initial for the following obtainment of the acting stress in the contact areas of rolling elements and races. The received data allow more accurate obtainment of the bearing life as a part of the specific rotor system. The developed means and analysis methodology are used to analyze the deformed and force state of the angular contact bearing of the high pressure compressor being the part of the test rig for investigation of the rotor support unit.*

ROTOR DYNAMICS, ANGULAR CONTACT BEARINGS, BEARING LIFE, DYNAMICS R4

## Introduction

Obtainment of life of rolling bearings mounted in rotors' supports has always been one of the priority tasks for the turbomachines designers. Displacements, deformations and loads should be found for almost every rolling bearing element in order to solve the task. It should be noticed that the values of all these parameters depend on the significant number of factors during the turbomachine operation. In particular, the bearing geometry, rotors speeds, weight force, radial and axial forces, temperature factors, presence of cooling liquid, etc. should be taken into consideration. The part of these data may be received easy enough from drawings, calculations, tests. At the same time some parameters may be found only considering the rotors dynamic behavior at unstable and non-linear statement. Nowadays this task is quite complicated, and designers virtually do not have any methodologies and means to solve it.

An attempt to solve the first part of this task is made in the present article; particularly to develop the methodology and algorithms for obtainment of displacements, deformations and reactions in rolling bearings (including intershaft ones) taking into account their geometry, the number of rolling elements, inertia, clearance and also those forced oscillations modes that the operating at the specific regime the rotor system has. At their basis the work of the setting's rolling bearings for testing the supports of the aviation engines should be investigated.

Resistance of liquid cooling the bearing is not taken into account when solving this task. This fact may rather change the obtained results. However, even at such statement we may approximate the actual stress in contact areas of races and rolling elements, and consequently, solution the task about bearing life also.

To solve the task the DYNAMICS R4 program system [1] for calculation and analysis of the turbomachine vibration characteristics is used. It includes the non-linear model of the angular contact (ball) bearing. The model allows obtainment of displacements, deformations and loads at five freedom degrees of rolling bearings being the part of the rotor system [2], [3]. Algorithms of transient analysis allow taking into consideration all variety of loading of the rotor system and rolling bearings at non-linear statement.

## Modeling of test rig

Fig.1 shows initial design of the test rig. The model of the rotor system was developed on its basis.

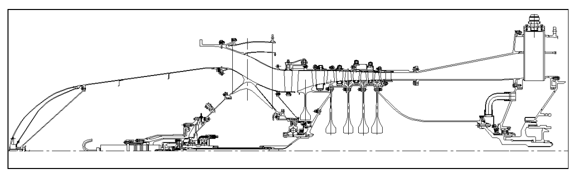

Fig. 1 Test rig design

The setting includes the case elements, the support unit including the angular contact bearing of the high pressure compressor (HPC), the support unit with the roller bearing, the HPC rotor with the technological shaft and the pin, the current collector supported by two ball bearings.

Fig.2 shows the main window of the DYNAMICS R4 program system with the model of investigated setting.

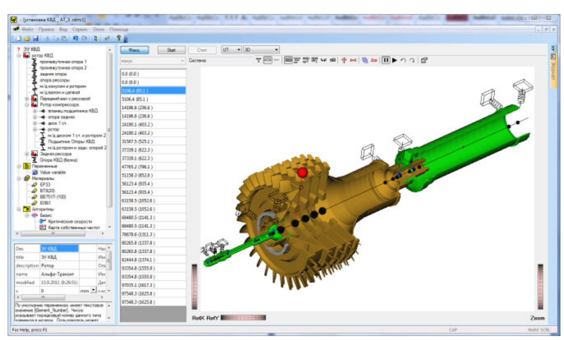

Fig. 2 Window of DYNAMICS R4 program system

All case elements are excluded from the model; their absence has a little influence on dynamic characteristics of the rotor system, results of analysis of the HPC bearing and does not change the task statement.

Fig.3 and Fig.4 show the model of the rotor system of the test rig.

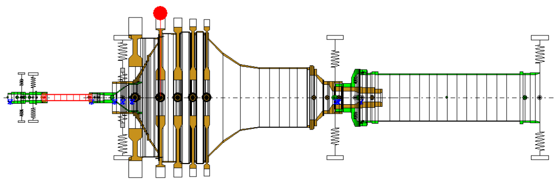

Fig. 3 Model of rotor system of test rig

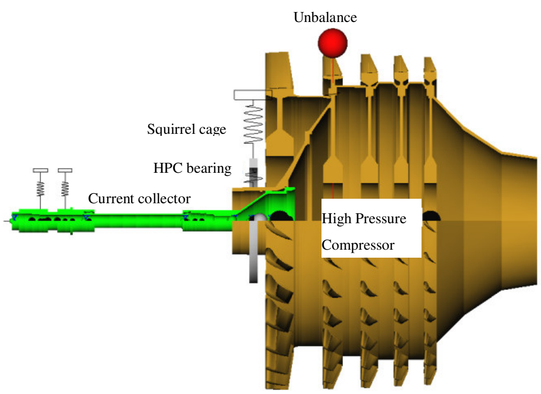


Fig. 4 Compressor part of setting model

Table 1 gives the initial data on the test rig and on the non-linear bearing.

Table 1

| | |
|---|---|
| Bore diameter of bearing on shaft, mm | 130 |
| Bore diameter of bearing on case, mm | 200 |
| Inner race diameter, mm | 145.024 |
| Outer race diameter, mm | 187.29 |
| Drawing radial bearing clearance in free state max…min, mm | 0.18…0.15 |
| Nominal contact angle, deg | 26 |
| Inner shaft diameter, mm | 116 |
| Outer case diameter, mm | 238.8 |
| Seating fit inner race/shaft max…min, mm | 0.013…0 |
| Seating fit outer race/shaft max…min, mm | 0…0 |
| Linear expansion coefficient, $deg^{-1}$ | $1.16*10^{-5}$ |
| Difference in temperatures between outer and inner race, °C | 0…40 |

Positions of curvature radiuses of races are set additionally, taking into account mounting fit and temperature conditions for inner and outer races of the HPC bearing. Curvature radiuses, axial force loading HPC bearing, unbalance of the compressor part of the rotor test rig are also given. Temperature regime is considered to be constant for all the investigated range of rotating speeds.

Detailed bearing drawings or information about the races parameters are necessary to set the bearing parameters. It is recommended to use the variant of the races parameters setting through coordinates of the races curvature centers. This variant is the most exact method of the setting of the bearing geometry and also the simplest when the bearing drawings are available.

Modeling the bearing as a part of the rotor, the following assumptions should be taken into account: every rolling element in the three-point bearing has only two contact points at operating mode; redistribution of axial force and change in contact at inner race does not take place.

Calculation results of the general characteristics of the non-linear bearing model are given below. General characteristics include: the bearing deformation along all the directions, force reactions of the bearing along all the directions.

Fig.5 shows the amplitude-time characteristic of the rotor system at the section of the rotor bearing of the HPC along Y-direction.

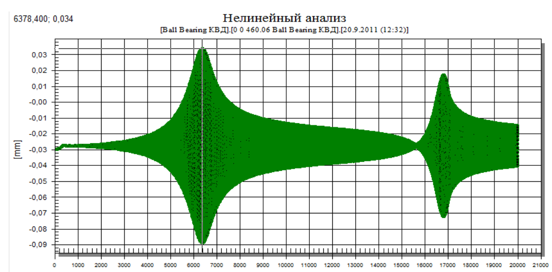


Fig. 5 Amplitude-time characteristics along Y-direction

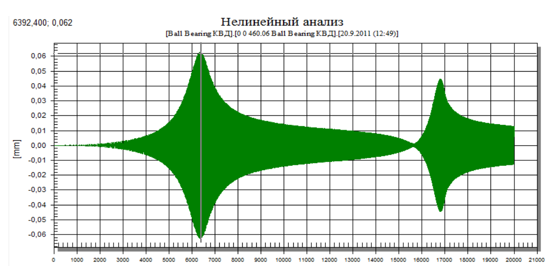


Fig. 6 Amplitude-time characteristics along X-direction (vibration displacement)

According to the obtained graphs, the rotor has two resonance regimes at about 6300 rpm and 16800 rpm.

The characteristics of the HPC bearings are shown below. They are obtained as a result of transient analysis of the rotor model with the non-linear HPC bearing under axial loading of 9800N, the compressor unbalance of 100gcm and taking into account weight force at different regimes.

There is the following format of output of analysis results: amplitude-time characteristics, output at any time point in a text format; possibility to obtain information graphically.

**Results of general analysis**

Fig. 7 and 8 show amplitude-time characteristics of the bearing deformation along Y,X directions correspondingly.

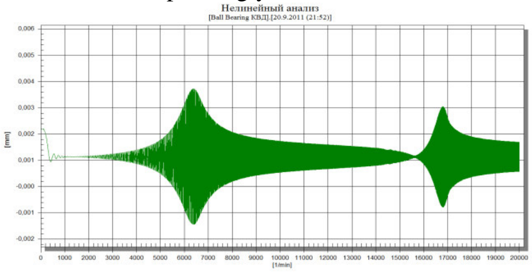


Fig. 7 Amplitude-Time characteristics at deformation (Y direction)

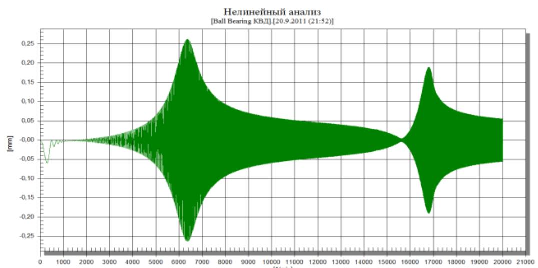


Fig. 8 Amplitude-Time characteristics at deformation (X direction)

Fig.9 and 10 show the bearing reactions.

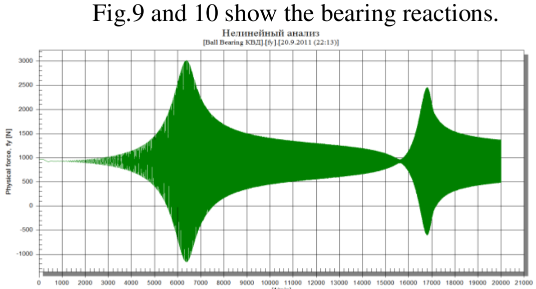


Fig.9 Bearing reactions along Y-direction

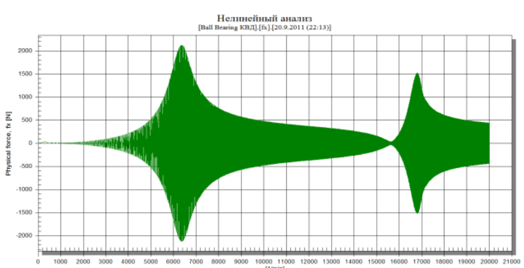


Fig. 10 Bearing reactions along X direction

Results of transient analysis of the rotor system with the non-linear HPC bearing being preloaded by axial force, dynamic load from the rotor unbalance and weight force allow estimation the bearing state at any of the setting operating modes.

A user can obtain distribution of the bearing reaction over rolling elements, deformations in contact points of rolling elements and the bearing races, contact angles at every rolling element in the bearing, location of the bearing races.

In the DYNAMICS R4 program system obtained results are output as data array in text format, Table2.

Table 2

| phi_i [град] | Deltai [м] | Gi [м] | Ge [м] | Q [N] | Alphai [град] |
|---|---|---|---|---|---|
| 9.00E+01 | -1.54E-05 | 7.83E-06 | 7.59E-06 | 1.05E+03 | -2.85E+01 |
| 1.10E+02 | -1.53E-05 | 7.76E-06 | 7.52E-06 | 1.04E+03 | -2.85E+01 |
| 1.30E+02 | -1.53E-05 | 7.75E-06 | 7.51E-06 | 1.04E+03 | -2.85E+01 |
| 1.50E+02 | -1.53E-05 | 7.79E-06 | 7.55E-06 | 1.04E+03 | -2.84E+01 |
| 1.70E+02 | -1.55E-05 | 7.89E-06 | 7.64E-06 | 1.06E+03 | -2.84E+01 |
| 1.90E+02 | -1.58E-05 | 8.02E-06 | 7.77E-06 | 1.09E+03 | -2.84E+01 |
| 2.10E+02 | -1.61E-05 | 8.17E-06 | 7.92E-06 | 1.12E+03 | -2.83E+01 |
| 2.30E+02 | -1.64E-05 | 8.33E-06 | 8.07E-06 | 1.15E+03 | -2.83E+01 |
| 2.50E+02 | -1.67E-05 | 8.48E-06 | 8.21E-06 | 1.18E+03 | -2.83E+01 |
| 2.70E+02 | -1.69E-05 | 8.59E-06 | 8.32E-06 | 1.21E+03 | -2.83E+01 |
| 2.90E+02 | -1.70E-05 | 8.65E-06 | 8.38E-06 | 1.22E+03 | -2.83E+01 |
| 3.10E+02 | -1.71E-05 | 8.66E-06 | 8.39E-06 | 1.22E+03 | -2.83E+01 |
| 3.30E+02 | -1.70E-05 | 8.62E-06 | 8.35E-06 | 1.21E+03 | -2.84E+01 |
| 3.50E+02 | -1.68E-05 | 8.53E-06 | 8.26E-06 | 1.19E+03 | -2.84E+01 |
| 3.70E+02 | -1.65E-05 | 8.39E-06 | 8.13E-06 | 1.17E+03 | -2.84E+01 |
| 3.90E+02 | -1.62E-05 | 8.24E-06 | 7.98E-06 | 1.13E+03 | -2.85E+01 |
| 4.10E+02 | -1.59E-05 | 8.08E-06 | 7.83E-06 | 1.10E+03 | -2.85E+01 |
| 4.30E+02 | -1.56E-05 | 7.94E-06 | 7.69E-06 | 1.07E+03 | -2.85E+01 |

The following notations are presented in the Table:

**phi_i** – angle that sets the position of the bearing rolling element in the Y-X section (around rotation axis);

**deltai** – deformations in points of contact between rolling elements and the bearing races, «–» sign means the presence of contact;

**gi** – deformation in the contact point at the inner race;

**ge** – deformation in the contact point at the outer race;

**Qi** – rolling elements reaction along the line connecting contact points of the rolling element (not taking into account inertia). If inertia of rolling elements is taken into consideration, the sum of reactions in contact points is output along the directions from contact points to the ball center.

**alphai(deg)** – contact angle of rolling elements, deg.

All the parameters in Table are output in the international system of units SI.

Deformations in the contact points of the rolling elements **deltai** at every rolling element may also be presented as a lobe diagram, Fig.11.

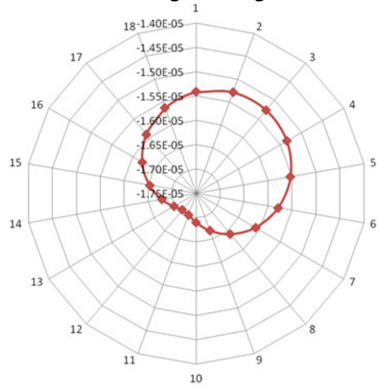


Fig. 11 Diagram of deformation in contact points at all rolling elements

Loads on rolling elements may be output similarly, Fig.12.

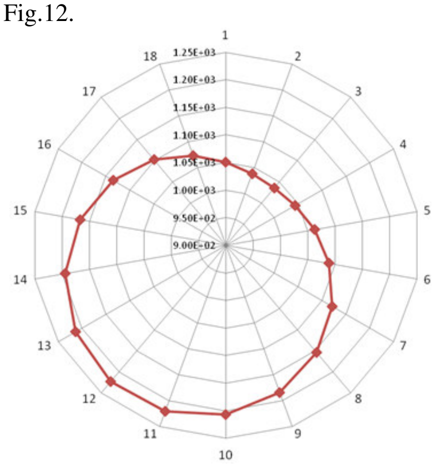


Fig. 12 Diagrams of loads acting on rolling elements

Loads at rolling elements may be output in all the range of rotating speeds as amplitude-time characteristic. As an example the loads for the ball located at Y-axis (Q_90) are output, Fig.13.

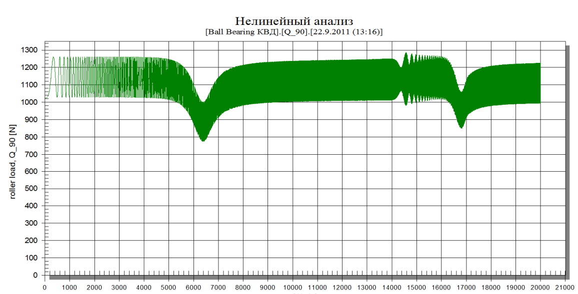


Fig. 13 Loads for ball located at Y-axis

Loads at all other rolling elements may be output similarly.

All the contact angles of rolling elements may be obtained in the lobe diagram by processing of the **alfai** column , Fig. 14.

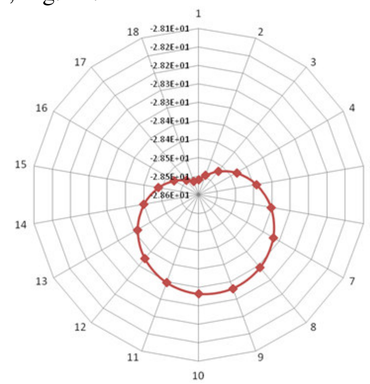


Fig. 14 Diagram of contact angles of rolling elements

**Displacements and loads of races**

For every chosen point the races displacements are output in the format presented in Table 3. It gives data at 14040 rpm.

Table 3

| | u | v | F |
|---|---|---|---|
| x1 | 4.19E-06 | 8.44E-03 | -4.18E+02 |
| y1 | -3.41E-05 | 6.18E-03 | 6.29E+02 |
| z1 | -1.89E-04 | -2.87E-04 | 9.66E+03 |
| r1 | -1.39E-05 | -8.63E-03 | -2.62E+01 |
| r1 | 4.79E-06 | 8.36E-03 | -1.91E+01 |
| r1 | 0 | 1.47E+03 | 2.08E-04 |
| x2 | 4.89E-06 | 8.26E-03 | 4.18E+02 |
| y2 | -3.27E-05 | 4.77E-03 | -6.29E+02 |
| z2 | 4.96E-10 | -7.80E-07 | -9.66E+03 |
| r2 | -3.50E-06 | 6.08E-04 | 2.60E+01 |
| r2 | -3.27E-07 | -9.99E-04 | 1.90E+01 |
| r2 | -4.83E-07 | 0 | -2.90E-05 |

Table 4 shows data for pass-through resonance regime of 6359 rpm.

Table 4

| | u | v | F |
|---|---|---|---|
| x1 | -1.57E-06 | -4.14E-02 | 4.73E+02 |
| y1 | 3.35E-05 | 4.35E-04 | -8.37E+01 |
| z1 | -1.89E-04 | -2.89E-06 | 9.81E+03 |
| r1 | 3.24E-05 | 2.05E-03 | -1.41E-01 |
| r1 | -4.91E-06 | 3.53E-02 | 2.57E+01 |
| r1 | 0 | 6.66E+02 | 4.15E-04 |
| x2 | -9.91E-07 | -3.97E-02 | -4.73E+02 |
| y2 | 3.21E-05 | 7.62E-04 | 8.37E+01 |
| z2 | -1.29E-09 | 2.59E-06 | -9.81E+03 |
| r2 | 3.42E-06 | 1.10E-04 | 1.44E-01 |
| r2 | -4.18E-07 | 4.23E-03 | -2.55E+01 |
| r2 | 1.72E-06 | 0 | -4.37E-05 |

Fig. 15…19 show linear and angular displacements of the bearing inner race in all range of rotating speeds.

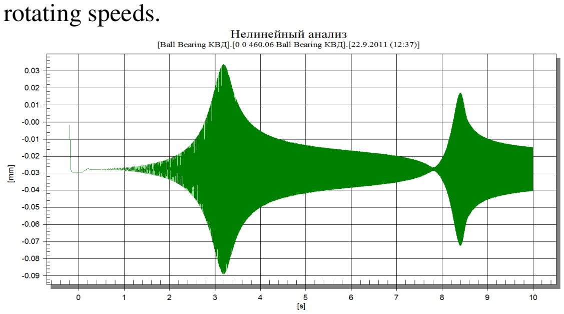

Fig. 15 Inner race displacement at Y-direction

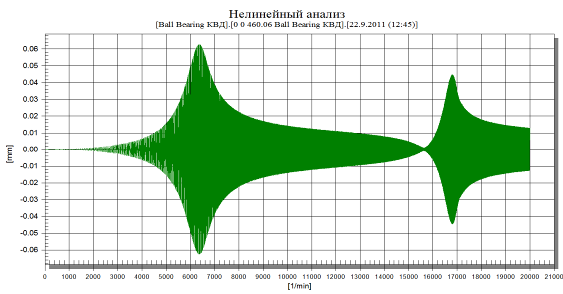

Fig. 16 Inner race displacement at X-direction

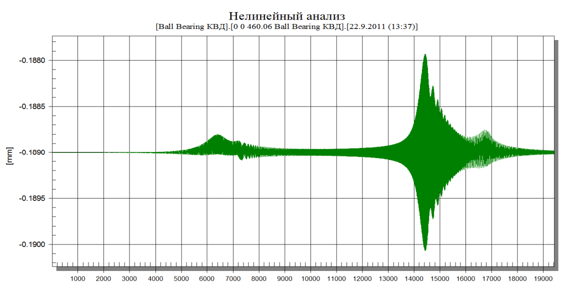

Fig. 17 Inner race displacement at Z-direction

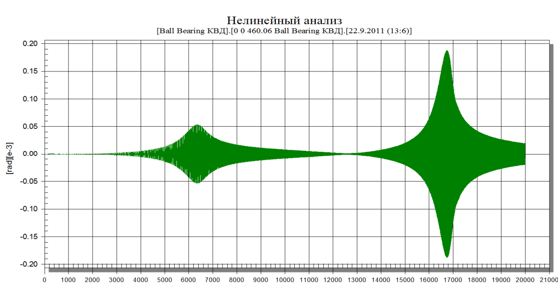

Fig. 18 Rotation angle of inner race around Y axis

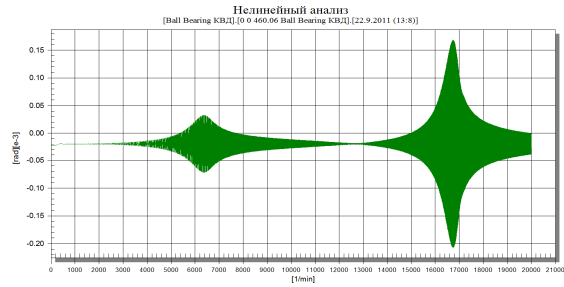

Fig. 19 Rotation angle of inner race around Y axis

Similar curves may be output for the outer race of the bearing set in the case supported by the spring element of the support structure.

Tables 5 and 6 give numeric values of the linear and angular displacements for the highlighted moments of time at the amplitude-time characteristics (regimes) for inner and outer races of HPC bearing correspondingly.

Table 5

| t[sec] | omega1 [rad/sec] | ux1[m] | uy1[m] | urx1[rad] | ury1[rad] |
|---|---|---|---|---|---|
| 0.40 | 8.38E+01 | -1.70E-09 | -2.77E-05 | -1.95E-05 | 1.05E-07 |
| 1.00 | 2.10E+02 | 1.70E-07 | -2.87E-05 | -2.06E-05 | -1.42E-07 |
| 2.00 | 4.19E+02 | -1.18E-08 | -3.40E-05 | -2.54E-05 | 3.80E-07 |
| 3.18 | 6.67E+02 | -1.23E-05 | -8.72E-05 | -6.95E-05 | 1.65E-05 |
| 4.00 | 8.39E+02 | -4.59E-06 | -4.90E-05 | -3.55E-05 | 6.07E-06 |
| 4.00 | 1.05E+03 | -3.89E-06 | -4.07E-05 | -2.68E-05 | 4.07E-06 |
| 6.00 | 1.26E+03 | -2.59E-06 | -3.76E-05 | -2.12E-05 | 2.01E-06 |
| 7.00 | 1.47E+03 | -1.94E-06 | -3.48E-05 | -1.19E-05 | -1.72E-06 |
| 7.50 | 1.57E+03 | -1.16E-06 | -3.20E-05 | -1.04E-06 | -8.64E-06 |
| 7.82 | 1.64E+03 | -2.59E-07 | -2.85E-05 | -3.46E-05 | -3.70E-05 |
| 8.40 | 1.76E+03 | -1.39E-05 | -6.70E-05 | -1.92E-04 | 6.59E-05 |

Table 6

| t[sec] | omega2 [rad/sec] | ux2[m] | uy2[m] | urx2[rad] | ury2[rad] |
|---|---|---|---|---|---|
| 0.40 | 0 | -7.26E-08 | -2.66E-05 | -2.83E-06 | 9.04E-08 |
| 1.00 | 0 | 1.55E-07 | -2.75E-05 | -2.94E-06 | 7.13E-08 |
| 2.00 | 0 | -4.48E-08 | -3.26E-05 | -3.47E-06 | 1.33E-07 |
| 3.18 | 0 | -1.23E-05 | -8.35E-05 | -8.89E-06 | 1.99E-06 |
| 4.00 | 0 | -4.63E-06 | -4.69E-05 | -4.00E-06 | 8.24E-07 |
| 4.00 | 0 | -3.91E-06 | -3.90E-05 | -4.16E-06 | 6.80E-07 |
| 6.00 | 0 | -2.66E-06 | -3.61E-05 | -3.84E-06 | 4.27E-07 |
| 7.00 | 0 | -2.00E-06 | -3.33E-05 | -3.55E-06 | 4.26E-07 |
| 7.50 | 0 | -1.21E-06 | -3.06E-05 | -3.27E-06 | 2.94E-07 |
| 7.82 | 0 | -2.67E-07 | -2.74E-05 | -2.92E-06 | 1.29E-07 |
| 8.40 | 0 | -1.43E-05 | -6.39E-05 | -6.80E-06 | 2.46E-06 |

Switching from the results of transient dynamic analysis of the non-linear bearing model as a part of the rotor system to the tasks of stress determination in contact areas of races and rolling elements and then to the tasks of the bearing life may be implemented by two ways, Fig.20.

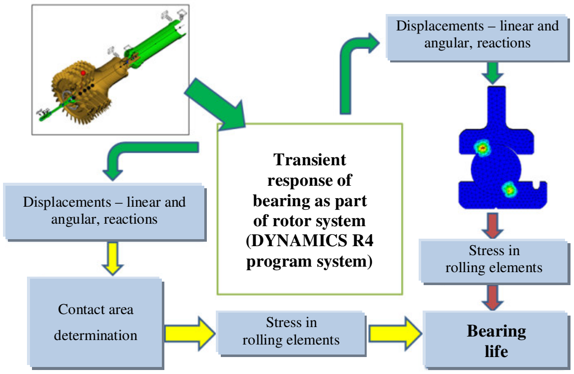


Fig. 20 Bearing life design procedure

The first way is by means of the DYNAMICS R4 program system. The second way is by means of the FEM programs; for them the obtained results are initial data.

**Conclusion**

The following conclusions have been made.

The methodology of deformed and force condition of angular contact bearings as a part of the rotor systems is developed. On its basis the bearing mathematical model and algorithms to analyze bearing as a part of a rotor system are developed.

The bearing model has 5 degrees of freedom, takes into account its geometry, the number of rolling elements, their inertia and clearance. Algorithms of the DYNAMICS R4 program system allow obtaining position of outer and inner bearing races for every regime with given rotating speeds, radial and axial forces, temperature and taking into account the rotor weight; Using the program, it is also possible to determine the contact angles and all force factors for every rolling element.

The received information is initial to determine the bearing life and allows its more accurate obtainment for the specific rotor system.

The developed means and analysis methodology are used to analyze the deformed and force state of the angular contact bearing of the HPC being the part of the test rig for investigation of the rotor support unit.

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