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Capabilities of estimation of rotor dynamic state on the ground of trajectories of bearing journals

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Abstract

In the paper presented are capabilities of advanced rotary machinery diagnostics based on the analysis of trajectories of slider bearing journals. Outlined and characterized have been the categories of rotary machine malfunctioning, which can be detected and discriminated on the basis of images of the journal center trajectory. Discussed have been these elements of trajectories, which bear information about the dynamic state of the machine and which can contribute to differentiation of the machine defects. Principles of diagnostics of the machine state have been analysed from the point of view of relations between the trajectory feature and the rotor dynamic state. Presented problems are based on author's own expertise and have been illustrated by sample images stemming from author's own experimental investigations as well as numerical simulations conducted using own computer codes. The material contained in the paper can be helpful in practical diagnostic applications.

Keywords: Journal bearing; Rotating machine; Technical diagnostics

1 Introduction

Trajectories of bearing journals contain a large amount of information both about operation of the bearings themselves, about the rotors and also about the dynamic state of the entire machine. In the motion of the journals reflected are the external forces acting on the rotor, as well as the internal ones – oil film reaction. The analysis of trajectory and the characteristic quantities determined on that basis can serve both for control purposes during the machine operation, particularly in transient states (start-up, changes of load, etc.) as well as can be used for diagnostic purposes [1-3].

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Capabilities of diagnostics of rotating machinery based on the trajectory of the bearing journals are undervalued. Machine diagnostics based on the journal trajectory is usually brought down to the assessment whether the trajectory changes or whether it falls in the tolerance limits determined by the designer of the control or diagnostic systems. Meanwhile information about the state of the machine is contained in many other elements of the trajectory. Important are among others mutual time relations between specific points of trajectory and their relations with the angular location of the shaft. Such relations are determined by the phasic displacement of trajectory points with respect to the base angular location of the shaft. Much information is brought by the shape of trajectory, for example its extension, slope, regularity of the shape [4-8].

In the paper presented have been selected principles and capabilities of diagnostics based on the analysis of bearing journal trajectories. The scope of the work has been limited to those problems, which could be confirmed by author's own expertise and illustrated by means of the results of own experiments or calculations. Sample drawings of trajectories have been performed on the basis of the results of experiments conducted on the research rig for investigations of rotors and bearings at the Rotor Dynamics Laboratory at the IFFM PAS in Gdansk and the results of computer simulations performed using the NLDW code developed for calculations of rotor dynamics using the non-linear methods [9-11]. In the paper outlined and characterized have been those classes of rotating machine malfunctioning, which can be detected by means of the analysis of the image of the journal trajectory [5, 11]. Described have been selected trajectory elements, which bear information about the machine dynamic state and on the basis of which various machine defects could be differentiated. The paper contains predominantly generalized information for practical application.

2 Elements of trajectories carrying diagnostic information

Instantaneous relative location of the journal centroid in the area of bearing clearance can be determined by geometrical summation of journal locations measured in two different directions. Such locations can be determined based on journal displacement with respect to two different displacement sensors situated in the same plane perpendicular to the journal rotation axis. Eddy current sensors for relative displacements are usually used for such kind of measurements.

Trajectory of the slider bearing journal is a set of instantaneous locations of its axis. An example of the bearing journal trajectory oriented in the coordinate system has been presented in Fig. 1. The trajectory can be characterized be some parameters, e.g.:

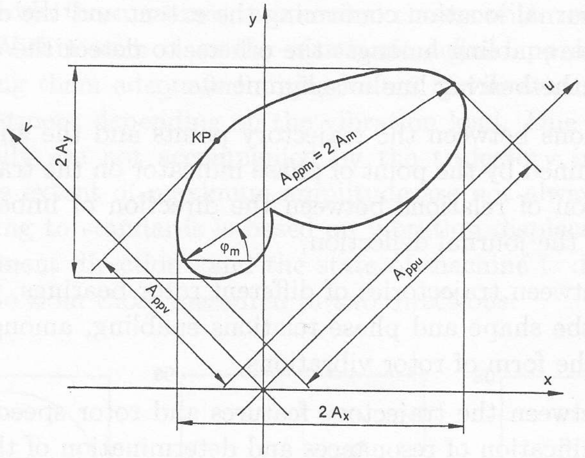

Figure 1. Elements of the bearing journal trajectory: A_x – amplitude of horizontal vibrations; A_y – amplitude of vertical vibrations; A_u – double amplitude of vibrations in the direction of measurement of u; A_v – double amplitude of vibrations in the direction of measurements of v; A_m – double maximum amplitude; φ_m – angle of inclination of maximum trajectory diagonal.

These quantities can be estimated based on the graph or calculated numerically, based on recording of vibration signals. The shape of trajectory, in principle, can be estimated by eye. When the trajectory is the ellipse then it can be characterized by the parameters describing the ellipse [7, 8]. The attempts of automatic recognition of the trajectory shape gave unsatisfactory results. A very important element of the measurement system linked to the trajectory analysis is the phase indicator (in Fig. 1 denoted as KP). This is the point on the trajectory image generated by the impulse coming from additional sensor at a specific angular location of the shaft. It synchronizes the location of the KP point in the graph with real angular location of the shaft.

The following elements and features of the trajectory of slider bearing journals can therefore be used for diagnostics of the dynamic state of machine rotor:

- trajectory dimensions, which contain information about the amplitude of journal vibrations in arbitrary direction, and indirectly about the extent of external and internal forces,
- form of trajectory, which enables to differentiate the origin and character of forces acting on the rotor, and in particular to conclude whether dynamic forces are external with respect to the bearing (excited vibrations) or internal (self excited vibrations),
- location of trajectory in the region of bearing clearance characterized by

the mean journal location confirming the extent and the direction of static bearing load, enabling amongst the others, to detect the bearing under or overload or the bearing line misalignment,

- phase relations between the trajectory points and the angular rotor position, determined by the point of phase indicator on the trajectory, enabling determination of relations between the direction of imbalance forces and direction of the journal deflection,
- relations between trajectories of different rotor bearings, particularly with respect to the shape and phase relations enabling, amongst the others to determine the form of rotor vibrations,
- relations between the trajectory features and rotor speed of rotation, enabling identification of resonances and determination of the resonance features.

Presented below principles of diagnostics of the state of rotating machines based on shaft trajectories have been described from the point of view of relations between trajectory features and the rotor dynamic state. The problem of diagnostics of the bearings themselves on the basis of trajectories of their journals has not been considered here. These are the problems specific to the hydrodynamic theory of lubrication.

3 Application of trajectories for diagnostic purposes

3.1 Dimension of trajectory – amplitudes of journal vibration

Dimensions of a trajectory enable to determine absolute amplitude of vibration in arbitrary direction. At that point revealed is the superiority of measurements of trajectories of rotating elements over the measurements of vibration amplitudes in specific direction themselves (in the direction of the sensor axis). Amplitudes of vibrations provide important information about the dynamic state of the bearing. These reflect dynamic forces acting on bearing bushes and bearing reactions acting on the bearing journals. Amplitudes of vibration can serve as the dynamic load indicator of rotating elements, as at specified frequency of vibrations the inertia forces of vibrating elements are proportional to the amplitude of vibrations [11, 12].

Methods of measurements of vibrations on rotating elements of machinery together with the criteria of assessment on that basis of the dynamic state of machines are governed by the standards from the series ISO-7919-1 . . . 4 and from the series ISO-10816. These standards determine the extent of admissible amplitudes of vibrations. From the point of view of hazards caused by vibrations the standards divide the machines into several classes with respect to their size and function. Within each class the standards define appropriate qualitative zones by assigning them adequate limiting values of vibrations and recommend the machine treatment depending on the vibration load. Due to that measured amplitudes usually are not accompanied by the trajectory images, hence the direction and the extent of maximum amplitude are not always known, the assessment according to standards is based on vibration displacement amplitudes "in the measurement direction" and the state of machine is determined by the greater amplitude from those measured in two directions.

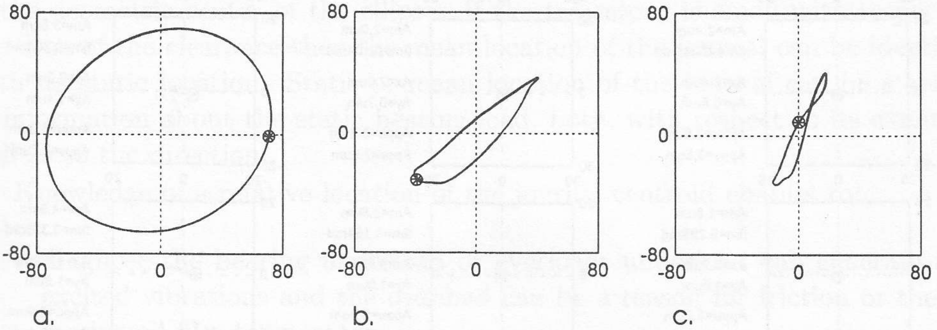

Figure 2. of different shapes of trajectories of bearing journals captured on the rig for investigations of rotor dynamics. Under the graphs presented are amplitudes of vibrations and the inclination of direction of maximum vibration:

a. $A_m = 76,3\mu\text{m}$, $\varphi_m = 31,2^\circ$, $A_x = 73,3\mu\text{m}$, $A_y = 67,8\mu\text{m}$, $A_{ppu} = 152,2\mu\text{m}$, $A_{ppv} = 128,1\mu\text{m}$;

b. $A_m = 52,7\mu\text{m}$, $\varphi_m = 40,3^\circ$, $A_x = 41,0\mu\text{m}$ $A_y = 35,6\mu\text{m}$, $A_{ppu} = 105,4\mu\text{m}$, $A_{ppv} = 26,2\mu\text{m}$;

c. $A_m = 40,7\mu\text{m}$, $\varphi_m = 65,7^\circ$, $A_x = 17,8\mu\text{m}$ $A_y = 37,2\mu\text{m}$, $A_{ppu} = 78,8\mu\text{m}$, $A_{ppv} = 33,2\mu\text{m}$.

In Fig. 2 presented have been three sample trajectories of slider bearing journal measured on the research rig for investigations of rotor and bearing dynamics, which works in IFFM Laboratory. Trajectories regard the same bearing under various conditions of machine operation. Below each trajectory presented have been numerically calculated amplitudes in the x, y, u, v directions together with the maximum amplitude. The direction of maximum vibrations is determined by the angle φ_m. The Fig. 2 presents the three, specially selected, basic shapes of trajectories. It is obvious that in reality trajectory shapes usually are irregular and can contain elements of the presented basic shapes.

The relative extent of the trajectory is determined by the ratio of trajectory dimension and the bearing clearance. This provides information about degree of the dynamic bearing load, expressed by the ratio of dynamic forces to the bearing static load. Amplitudes of journal vibrations without corresponding graphs

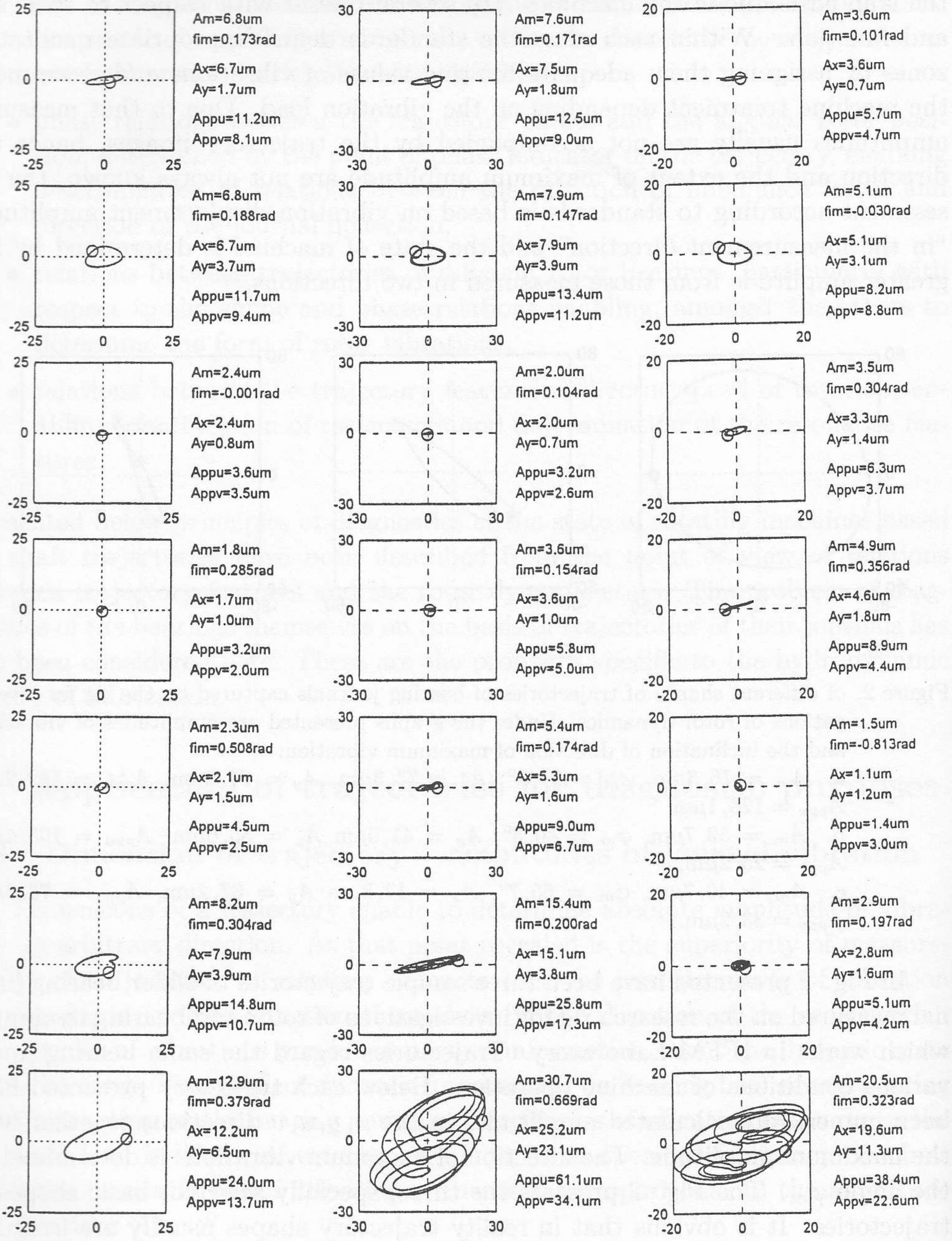

Figure 3. Influence of bearing displacements on the trajectories of bearing journals in the large turboset. Trajectories have been obtained on the basis of computer simulations. In rows from the top – subsequent bearings No. 1 to 7. Column 1 – reference case, bearings situated in the geodesic line; column 2 – bearing No. 6 shifted by 5 mm upwards, column 3 – bearing No. 6 shifted by 2.5 mm left.

of trajectories do not provide information about the character and the origin of dynamic forces. These can be rendered by the external excitations (excited vibrations) or the internal forces generated in the bearing (self excited vibrations). For their differentiation required are additional information, which can be contained in the trajectory shape itself.

3.2 Location of trajectory in the region of bearing clearance

If the trajectory is a regular closed curve, for example ellipse, then it can be assumed that the mean location of the journal in the region of bearing clearance is the geometric center of the ellipse. If the trajectory is small with respect to the area of the clearance then the mean location of the journal can be identified with its static location. Static or mean location of the journal can be a source of information about the static bearing load, both, with respect to its extent as well as to the direction.

Knowledge of a relative location of the journal centroid enables to:

- diagnose the bearing underload or overload; underload can generate self-excited vibrations and the overload can be a reason for friction or the excessive oil film temperature,
- revealing of the bearing misalignment (if there are more than 2 bearings), which renders that the bearings influence each other,
- revealing of the extent or the direction of bearing static load due to the change of forces acting on the rotor.

3.3 Influence of dynamic forces on the trajectory shape

By the trajectory shape must be understood both the geometric figure, which is represented by the trajectory, and its orientation in the plane. A significant change of the trajectory shape serves as an important diagnostic signal and ought to be sorted out [4, 9].

The journal trajectory of correctly operating bearing should be a small (with respect to the bearing clearance area) ellipse. The journal centroid performs in such a case a precessive motion, which is usually synchronous with the revolutions. Such motion is rendered by the rotor residual imbalance and in practice is not to be avoided. A large trajectory with respect to the bearing clearance, which reminds with its shape a circle, confirms a significant rotor imbalance. An example of such trajectory is presented in the first distribution in Fig. 2. The radial bearing clearance reaches in that case 80μm and the trajectory diameter 70μm respectively. Irregular, sharp-edged trajectories in the form of triangles or intercepting polygons, as shown in the second distribution in Fig. 2, confirm usually the friction between the rotor elements and stationary elements. Trajectories in the form of closed curves with wavy character or in the form of intercepting lines forming loops certify the existence of such excitation forces of which the frequency is the multiple of rotor rotational velocity. An example of such trajectory is presented in the third distribution in Fig. 2.

The source of periodical forces, where the frequency is the multiple of rotor rotational frequency, can be the rotor geometric asymmetry or non-linearity in its stiffness characteristics. Geometric asymmetry is characteristic to the generator rotor. The generator sometimes is the source of dynamic forces with frequencies twice greater than the rotor rotational frequency. Then it can generate trajectories resembling figure of eight. Trajectories with a similar shape can also be rendered by the non-linearity of stiffness characteristics. It can reveal in the case of significant lateral rotor shaft vibrations. Both of these contributions, i.e. axial rotor asymmetry and the non-linearity of stiffness characteristics take place as a result of the shaft crack. In that case, for the diagnostic purposes, are useful information borne by the phase indicator. The trajectory shape in combination with the location of the phase indicator enables to conclude about the place where the crack takes place.

3.4 Influence of static forces on the trajectory shape

If the rotor is supported in more than two bearings, then the bearings can load each other. In such case the static location of the journal in the bearing clearance area and the trajectory shape in one of the bearing influences the journal location and the trajectory shape in other bearings in the way dependent on the shaft stiffness and the extent of displacement. The nominal static load of bearings takes place when these are aligned in a precisely specified line. The bearing displacement with respect to this line can occur for example during the overhaul or as the result of thermal deformations of bearing supports or foundation or due to the foundation subsidence. A significant static bearing load reflects with flattening of trajectory in the direction of force causing the load.

The influence of bearing displacement on the trajectory shape is illustrated in Fig. 3 on the example of turbine of 200 MW power [13, 14]. The trajectory distributions have been graphed based on the results of computer simulations of the displacement effect of bearing No. 6 of a turboset using the NLDW code. In particular rows of the graph presented have been the trajectory images of seven turbine bearings. The first column contains trajectories for the base case, where the bearings are situated on the rotor geodesic line. Trajectories in the second column have been obtained at the displacement of bearing No. 6 by 5 mm upwards. As can be seen, the trajectory of bearing journal No. 6 got strongly flattened due to the journal tightening to the lower half-bush. Meanwhile the bearing journal No. 7 has been shifted upward and relaxed. This rendered instability of its operation in the form of oil whip. Trajectories of remaining bearings, located at some distance from the bearing No. 6 did not undergo significant changes. The third column contains the trajectories after horizontal shifting the bearing No. 6 by 2.5 mm. As this is the bearing with the lens-shape clearance, vibrations of that journal practically disappeared. At the same time, however this rendered an unstable operation of bearing No. 7, which is cylindrical. The image of bearing No. 7 trajectory is the example of fully developed oil whip. The reason for it is relaxation of that bearing due to shifting of neighboring bearing as well as the fact that the bearing No. 7 is cylindrical and hence its damping capability is small. Hydrodynamic instability is characteristic just to the bearings weakly statically loaded.

3.5 Identification of shape or modes of rotor vibrations based on trajectory

Based on recorded trajectories of rotor elements, it is possible to determine instantaneous shape of the rotor axis and hence the dominating form of vibrations [11, 15]. Determination of the form of rotor vibrations based on trajectory is only possible when the trajectories of particular rotor elements are exactly synchronized by the points of phase indicator on the trajectory graphs (point KP in the Fig. 1). Trajectories must provide information about the phase lag of corresponding points KP marked on the two trajectories measured on the opposite sides of all bearings. It is also necessary to adequately distribute along the rotor length a sufficient number of probes for trajectory recording.

Realization of such kind of measurements in practice is difficult. Sensors for vibration control of large machine, mounted in a standard way, are not sufficient as these are usually mounted on one side of the bearing bushes. It is necessary to mount additional pairs of sensors distant apart from the bearings as much as possible. Usually the rotor beyond the bearing is inaccessible and hence in practice these must be additional sensors fixed to the bush on the opposite side of bearing.

In Fig. 4 presented has been the result of realization of such identification based on the trajectories of rotor of the research rig for investigations of rotor and bearing dynamics, exploited in IFFM PAS. Determination of the form of vibrations in that case was facilitated, as it was possible to utilize the shaft trajectory in the middle between the bearings. In Fig. 4 presented are trajectories of the rotor axis in five planes along the rotor axis length: journals of three bearings and 2 points in the middle distance between bearings. Below are given the projections: horizontal and vertical of the shaft deflection line rotating with the

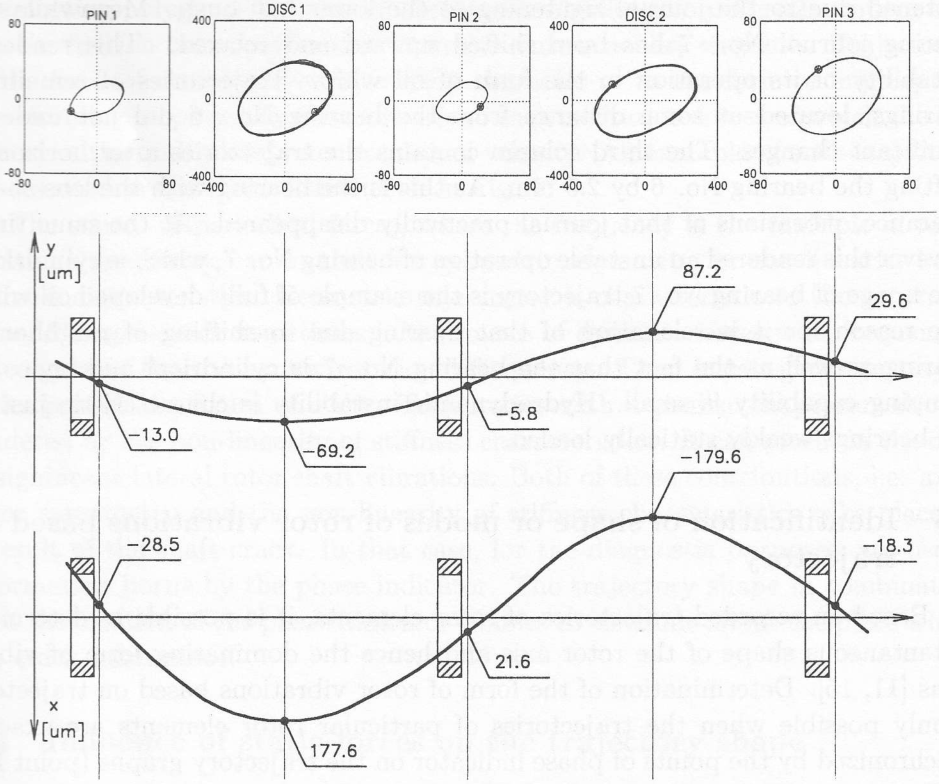

Figure 4. Illustration of the way of determination of the form of vibrations on the basis of trajectories of the shaft elements: top – trajectories of bearing pins and of the rotor between bearings; below – horizontal and vertical projection of the axis of deformed rotor at the instant determined by the point in the graphs of trajectories.

velocity of 2784 rev/min. The scale of transverse displacements in characteristic points has been preserved and the figure represents a real shape of the shaft. The shaft has such a shape at an instance when the rotating imbalance crosses the positive horizontal coordinate. That moment in the figures of trajectories is accompanied by the points denoted with circles. Based on the distribution of the line of shaft deflection it can be concluded that the obtained shape represents one of the first form of shaft free-vibrations. This corresponds to the frequency of 43.3 Hz, which results with the rotor critical velocity of 2880 rev/min.

The shape of the line of shafts enables to assess the form of rotor vibrations and linking it to the frequency of that form. Knowledge of the shape of rotor enables also to balance precisely the rotor mounted in the machine as it enables estimation of the direction of forces acting on the rotor.

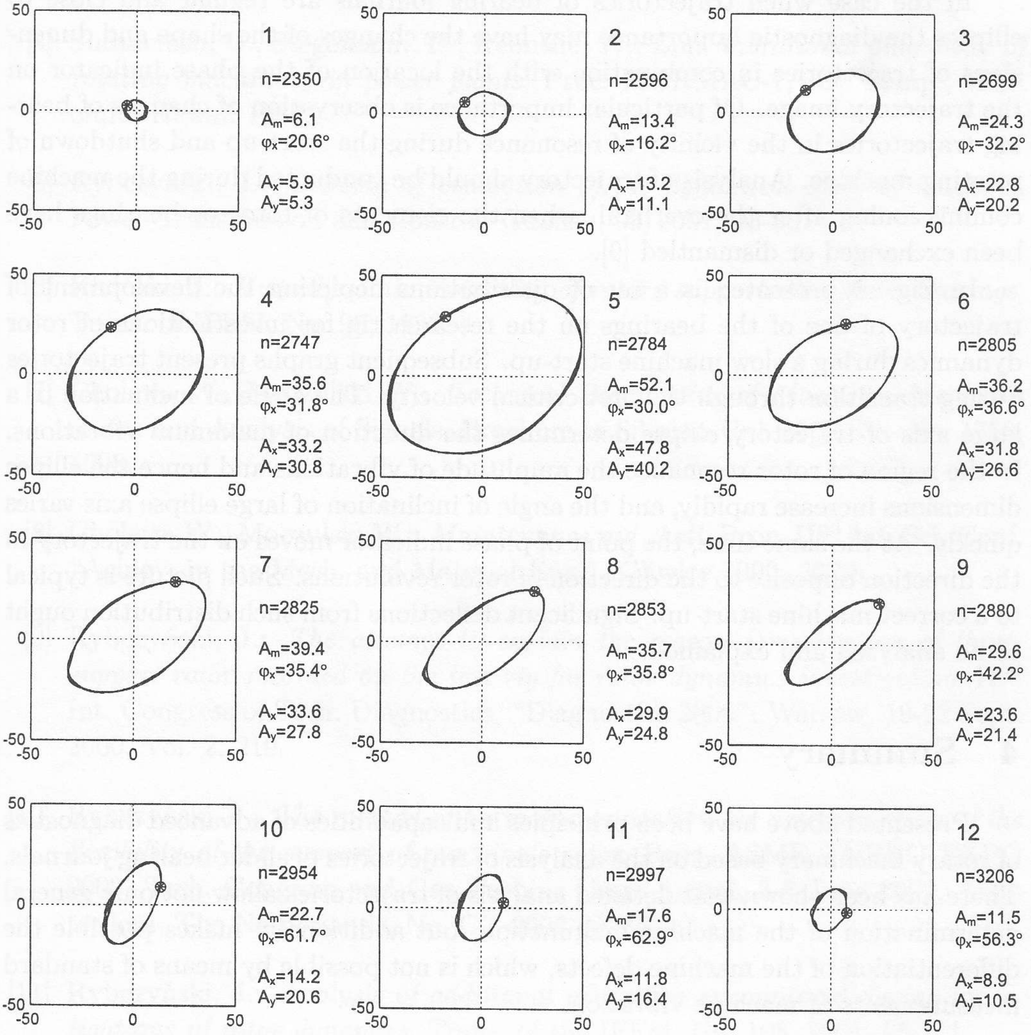

Figure 5. Development of trajectory in one of the bearings in the research rig for rotor dynamics investigations during the machine start-up in the vicinity of first critical velocity. Notation: n [rev/min] – rotational velocity; A_m [μm] – maximum amplitude; φ_m – the angle of inclination of trajectory maximum diagonal; A_x [μm] – amplitude of horizontal vibrations; A_y [μm] – amplitude of vertical vibrations.

3.6 Slope of journal trajectory and location of phase indicator

In the case when trajectories of bearing journals are regular and close to ellipses the diagnostic importance may have the changes of the shape and dimensions of trajectories in combination with the location of the phase indicator on the trajectory image. Of particular importance is observation of changes of bearing trajectories in the vicinity of resonance during the start-up and shutdown of rotating machine. Analysis of trajectory should be conducted during the machine commissioning after the overhaul, when the elements of rotor or bearings have been exchanged or dismantled [9].

In Fig. 5 presented is a set of distributions depicting the development of trajectory of one of the bearings on the research rig for investigations of rotor dynamics during a slow machine start-up. Subsequent graphs present trajectories during transition through the first critical velocity. The angle of inclination of a large axis of trajectory ellipse determines the direction of maximum vibrations. In the region of rotor resonance the amplitude of vibrations and hence the ellipse dimensions increase rapidly, and the angle of inclination of large ellipse axis varies quickly. At the same time, the point of phase indicator moves on the trajectory in the direction opposite to the direction of rotor revolutions. Such picture is typical to a correct machine start-up. Significant deflections from such distribution ought to be analyzed and explained.

4 Summary

Presented above have been principles and capabilities of advanced diagnostics of rotary machinery based on the analysis of trajectories of slider bearing journals. There has been shown that detailed analysis of trajectories allow not only general determination of the machine malfunction, but additionally makes possible the differentiation of the machine defects, which is not possible by means of standard measurements of machine vibration.

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