Development of methodological support for turbine unit shaft defect and stress monitoring systems at thermal power stations and atomic power stations with application of shaft displacement sensors*)

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Abstract

It is proposed a modern concept and a set of methods for monitoring of the technical condition of system "turboset's shafting – journal bearings – support units". Technology is developed as an integral part of domestic multipurpose COMPACS® system®. The system input data covers: - design, technological, mounting and operating parameters of the turbine unit; - absolute vibration of supports and control points of the shafting line; - relative displacement and vibration in the rotor journals according to GOST R 55263-2012. Also, the system includes as precomputed: - mounting line of the shafting in cold state; - for each journal bearing, static and dynamic properties of the bearing oil film in domain of possible motion (DPM are given; - static and dynamic properties of supports; - matrix of influence of displacements of supports on the forces in supports of the shafting.

While in operation, the methods allow to determine static and dynamic loads on the supports of turboset, to determine misalignment of supports and to evaluate corrective alignments of the supports and centering of coupling halves. Also, stress in the rotor pins, welded joints and coupling bolts are computed.. We suggest an automatic conclusion on compliance of the technical condition of turboset with safety levels, identification of source of malfunction and recommendations for necessary measures. The work covers some procedures, including ways of determination of stiffness of supports, a method of determination of above mentioned matrix of influence and a method of inverse problem solution – determination of misalignments of the supports based on determination of position of rotor journals in the bearing bores.

We have shown the results of static characteristic modeling by an example of turbine unit 1000 MW for atomic power stations.

Keywords: *shafting line, support, turbine unit, oil film, bearings, static and dynamics properties, misalignments of supports, alignments of the rotors, stiffness matrix, stress, the shaft sensors, monitoring of technical condition.*

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1. Introduction.

The control systems for safe resource-saving operation of the equipment (ASC BER COMPACS®) [1,2] applied in different industries can work with any sensors, including shaft movement ones [3]. Static and dynamic shaft movement is sensitive to most defects in multiply supported rotor systems with journal bearings. Their application in monitoring systems allows to make visible invisible before process. Shaft sensors determine motion of neck of rotor both in vertical and in horizontal direction. For this purpose according to ISO [8] only two gap sensors are installed in one cross-section. Two sets of shaft sensors per one support bearing, installed at both sides of bearing, is more advanced setup, known as complete set of shaft sensors [4,5]. Usually, shaft sensors are used to measure absolute vibration and (optionally) to measure displacement of shaft's neck from rest mode to operation mode ("floating-up displacement"). Complete set of shaft sensors enables to measure angular misalignments of shaft necks and to monitor clearances much more precisely. The Russian Federation standards base [3,7] goes ahead of the proper standard ISO [8] in part of sensor application but has no complete procedural part, including for fault diagnostics. The system condition can be specified by its static and dynamic properties, including static and dynamic minimal clearances, oil consumption, friction loss, maximal temperature of oil and babbitt, static reactions and support misalignment; level and spectral composition of the support and shafting line vibration, touch probability, resonance tune-out, imbalance residual dynamic reaction of supports, etc.

The basic information on the static properties metered by shaft sensors (floating-up curve, minimum clearances, etc.) and on other relevant properties (parameters of bearing capacity, frictional loss, rotor misalignment, stiffness and damping of oil film, etc. [7,12]) in the monitoring systems at thermal and atomic power stations is not used and not analyzed. Some foreign companies apply floating-up curves to diagnose different machines, but they cannot go beyond the challenges specified in [8]. According to this standard, only one pair of sensors is installed to determine static displacement of the shaft. However, because of angle misalignment of the rotor journals with respect to the bearing axis appearing due to misalignment of supports and bite of the stator elements while the turbo unit heating, it is impossible to evaluate the support correct condition with one pair of sensors. The only exception is turbo units of Hungarian atomic power station PAKSH. Such turbo units have two pairs of shaft sensors on each bearing that allows, during their adjusting, to see and eliminate imbalance of journal necks in bearing bores. However, we know no systems where support misalignment can be specified under results of the shaft displacement measurement.

The problem of evaluation of the support current misalignment and, properly, of the turbine unit rotors is one of the most important and complicated in technical condition diagnostics. Until recently, misalignment has been measured with special means [17]. Since the 1960s, when Lisitsyn I.S. for the first time measured support height displacement (HDS) with the help of water level gauges for turbine unit 300 MW in its transition from cold state to hot state, this method has been improved by different companies: CDB ENERGOREMONT, VTI, LMZ, SibAtomGeo, MPEI. However, the HDS is very hard to be measured with all metering ways, and permanent control cannot be provided. While real-life experience says that even in aseismic regions supports can settle down for various causes within a short space of time.

In the COMPACS® project it is supposed that misalignment and correcting alignment are to be diagnosed completely in automatic mode [1]. The whole system of shaft sensors simplifies automatic search for residual damage after the unit assembly [7]. And the scope of information received from the shaft sensors and the developed criteria set allow to evaluate danger or permissibility of discovered defects also in automatic mode [7] and to evaluate the technical condition more seriously.

In such a way, we can solve the following new problems:

- COMPACS® adaptation for power plants with a complete or partial set of shaft sensors mounted in journal bearings;
- development of the methods, including development of diagnostic signs of power plant damage and their automatic determination, as well as solution of a series of auxiliary diagnostic problems;
- check and optimization of diagnostic signs by means of physical and mathematical modeling;
- improvement of the standards base, including technical requirements to vibration control systems, to monitoring and diagnostics of different turbine units.

2. Development of methods for shaft damage and stress monitoring systems within supports operational misalignment

The problem-solving method for damage diagnostics during manufacturing, mounting and operation of power equipment is based on the results of monitoring static and dynamic displacement of rotor journals in combination with methods of calculation of dynamic properties of rotors and supports applied for designing. Shaft displacement causing all other main rotor disturbances is sensitive to many defects like defects of rotor assembly in coupling halves, rotor alignment in the wheel space, supporting defects, etc.

All causes of unsatisfactory technical condition can be divided into a few common groups:

A) **Design causes** specifying inborn defects or design features. Among such causes can be design uneven stiffness of individual elements, their insufficient resonance grading, increased static or dynamic loads, low level of system damping, excessive wear, traditional small clearances in bearings of some manufacturers, etc. All these causes can both worsen the technical condition and shorten the resource, as well as can demand special measures for their compensation or for lowering their effect onto workability;

B) **Technological causes** can appear on all technological stages, from basic component blanks manufacturing to basic details and turbine units mounting and testing.

C) The third group of causes appears while in operation, within the process of wear, surface degradation, residual deformation, soil and foundation settlement caused by watering and seismic effects, etc. Let us call them **operational causes**.

All listed causes are connected to proper defects and, as they develop, can interact and strengthen each other.

In traditional systems of vibration control, monitoring and diagnostics [9,10] all these cause were impossible to be monitored as the problems were no set and solution ways were not developed. The ideology and systems which we offer allow to control the processes in the rotor systems and consequently to control the equipment reliability.

To adapt the COMPACS® system for monitoring of large power plant technical condition, it is necessary to solve the next key methodological and technical problems:
– automation of search and evaluation of residual defects of rotor manufacturing and assembling, and development of criteria to evaluate their danger or permissibility.
- development of methods, development of diagnostic signs of power plants damage by means of shaft sensors for their automatic detection, and solution of auxiliary diagnostic problems;

- check and optimization of diagnostic signs by means of physical and mathematical modeling;
- improvement of specifications for systems of vibration control, monitoring and diagnostics of various turbine units.

A few solutions of the abovementioned problems are partly given in [7,8,11-14].

The list of diagnosable defects and criteria of error-free operation of the turbine unit supports and shafting line with application of the shaft sensors full set are given in [8]. An updated method to specify support reaction from operational misalignment by interpolation in the field of the shaft journal possible displacement is shown in [11,12]. Dynamic loads in the shafting line supports and their diagnostics are considered in [5]. Further we will cover a few methodological issues, including solution methods of the inverse problem: determination of support misalignment under the rotor journals relative positions measured in bearing bores.

2.1. *Static loads and stress measuring methods for shafting lines in operation.*

In this section we will talk about monitoring and diagnostics of thermomechanical effect due to support misalignment. We suggested pre-calculation of dimensionless discrete vector fields of displacement and proper dimensionless loading, as well as other static properties of oil film, to speed up calculation of the shafting element stress while in monitoring in [7,11,12]. Also, the shafting stiffness matrix, due to support single displacements, can be pre-calculated (see an example in section 2). This data is included in the knowledge base of the monitoring system COMPACS®.

We shall consider the space assembling line of the multiply support shafting in hot state (fig. 1). It meets the support position vector (bearing bore centers) $\bar{h}$. The global vector $\bar{h}$ consists of 2n elements, where n is the supports number:

$$\bar{h} = [h_{11}, h_{21}\ h_{12}, h_{22} \ldots\ldots h_{1j}, h_{2j} \ldots\ldots\ldots h_{1,n-1}, h_{2,n-1}\ h_{1n}, h_{2n}]^T. \qquad (1)$$

The first index 1 refers to the horizontal plane in cross direction, index 2 refers to the vertical plane. We will differ such a line, according to [13,14], in two states: an ideal assembling line (dash line) when coupling bolt stress after the shafting line has been assembled in hot state, after floating-up on the oil wedge is equal to zero; and an actual assembling line (thin line) received after assembly of the shafting line with residual misalignment of rotors according to coupling halves because of difficulty to "guess" the support optimal position.

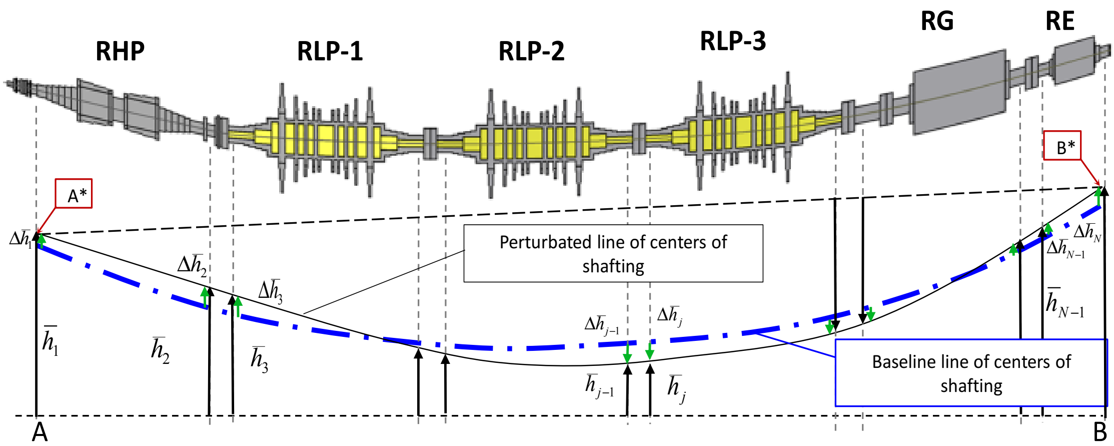

Fig. 1 The ideal and the actual shafting lines

The support ideal position meets the calculated position of the shaft in the bearing bore with necessary factor of loading capacity. Vector $\Delta\overline{h}$ features a derivation of the actual line from the ideal one. One of the key problems is determination of this vector to calculate corrective alignment of rotors according to coupling halves and to achieve their position close to ideal by means of the support position correction ().

[14, 15] offer an advanced method for determination of the shafting stiffness matrix $[G]$ which can be obtained with successive single displacement of supports horizontally and vertically. Earlier, such a matrix was calculated for a shafting on rigid supports, but as it is shown in [15] consideration of oil film compliance makes the stiffness factor over two times less.

The physical meaning of factors *G (i,j)* is that they are equal to additional loads to the rated reaction in support *i* in kN obtained at a single displacement of support *j* horizontally or vertically in mm. This matrix unambiguously connects the vector of displacement of the bearing bore centers from the ideal line $\Delta\overline{h}$ to the vector of additional cross static forces $\Delta\overline{Q}$ in supports:

$$\Delta\overline{Q} = [G]\Delta\overline{h}\,. \qquad (2)$$

Cross loads additional to the rated ones $\Delta\overline{Q}$ in each j bearing are determined as follows. At any time, static displacement measured at both sides of the bearing are averaged and reduced to their transverse axes in the form of eccentricity vectors e_j. Then they are reduced to dimensionless eccentricity and on the diagram [7] you can find proper loading vectors. An increment of the loading vector specifies dimensional loads additional to the rated ones $\Delta\overline{Q}$ j in the supports which later are used for misalignment calculation (see ratio 2).

2.1.1 Solution method for the direct problem of determination of the shafting actual line, rated and actual loads in supports and stress in shafting elements.

The direct problem and options are formulated as follows. Suppose we know design, technological, mounting and mode parameters of the turbine unit rotors and bearings including: shafting mounting line in cold state; rated parameters of rotor journals positions on the mobile equilibrium curve; static properties of oil film of journal bearings for random position of the rotor journal in the bearing bore, support static yield, support misalignment and corrective centering rotors according to coupling halves, oil properties, etc.

It is necessary to calculate: a) the shafting line for ideal case in hot state;

b) actual static reactions in supports for given misalignment;

c) conformance of corrective alignment to ideal alignment when they completely compensate support misalignment and different floating-up of adjacent rotors in hot state and provide absence of displacement in cross-sections on rotors joints:

d) stress in rotor journals and coupling bolts due to misalignment and rotor dead weight.

General packaged **super-element** approach for determination of support reactions, forces, moments and stress in shafting elements in case of its supports misalignment [15] considering optimization under [11,12] with proper boundary conditions in horizontal and vertical planes is applied for solution of these problems. As factors of the oil film flexibility matrix [D_M] are nonlinear and depend on loads in supports, we apply the iteration method like in [15]. For k bearing the matrix shall be determined with 4 factors of nonlinear static flexibility

$$[D_M]_k = \begin{bmatrix} e_{M11} & e_{M12} \\ e_{M21} & e_{M22} \end{bmatrix}_k . \quad (3)$$

$[D_M]_k$ connects the vector of position of k neck of the shaft in bore $\overline{e}_к$ and the force vector in oil film $\overline{Q}_к$

$$\overline{e}_к = [D_M]_к\ \overline{Q}_к . \quad (4)$$

Vectors of displacement $\overline{e}_к$ are counted out form the bearing center. Factors of static flexibility matrixes $[D_M]_к$ are determined by the interpolation method under [11,12]. Fig. 2 shows an example of interpolation of floating-up properties with use of proper fields of displacement and loading for bearing No. 8 of turbine unit K-1000/65-1500.
For initial approximation of support reaction we shall determine, at a first approximation, the oil film flexibility matrix $[D_M]_k$ and the integral matrix of stiffness $[C]_k$ for each support considering compliance of the very support. After transverse forces and moments have been determined, we shall calculate stress in rotor journals, welded joints and coupling bolts in known conditions of bolt tightening and geometry. Generally, when calculating stress, we shall consider additional external forces, for example, in the governing stage.

2.1.2 Determination of the shafting stiffness matrix.

The shafting stiffness matrix [G] from single displacement of supports defining sensitivity of rotors to misalignment is determined in the way similar to other direct problems. For determination of k- column of the stiffness matrix $[G]$, it is necessary to define a single disturbance on the k- support vertically or horizontally. Matrix $[G]$ allows to evaluate additional vectors of static forces in supports at the given values of support displacements.

Table 1 shows the complete matrix for fourteen-support shafting system of turbine unit 1000 MW block by block as an example. Symbols dy1..dy6,dx1,..dx14 in the column name indicate the support number (1 to 14) and displacement direction (x or y). In the same way, names of lines ry1..ry6,rx1..rx14 indicate the support number and force direction to calculate an element of the influence matrix. This matrix has the size (28*28) and, in cross sectional factors, considers additional forces arising in the horizontal plane from vertical single displacements, and vice versa. It is clearly that static disturbance decays actually in 2-3 supports from the displaced one. However, there is significant connection between vertical and horizontal displacements.
Table 1 shows significant vertical reactions caused by single horizontal displacements.

When adjusting turbine units, such matrix can be recommended for evaluation of consequences after correction of rotor alignment and intuitive displacement of supports during the turbine unit adjustment. The full matrix of such a type has been constructed for a shafting line for the first time.

Table 1. Matrix of stiffness for the vertical (y) and horizontal (x) planes (kN/mm), shafting line of turbine unit 1000 MW, 14 supports at single displacement of support 1 mm.

(a) Additional vertical forces at vertical displacement of supports 1 to 14

sens	dy1	dy2	dy3	dy4	dy5	dy6	dy7	dy8	dy9	dy10	dy11	dy12	dy13	dy14
ry1	11.40	-41.07	32.27	-1.64	-1.06	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ry2	-40.93	232.11	-244.68	44.26	11.52	-1.61	-0.61	0.04	0.02	0.00	0.00	0.00	0.00	0.00
ry3	32.07	-244.38	313.14	-149.55	43.57	5.78	-0.77	-0.25	0.01	0.01	0.00	0.00	0.00	0.00
ry4	-1.49	42.64	-145.21	523.61	-479.43	41.16	21.63	-0.74	-0.84	0.01	0.02	0.00	0.00	0.00
ry5	-1.13	12.76	40.01	-480.48	536.00	-155.47	39.69	8.15	-0.43	-0.37	0.02	0.00	0.00	0.00
ry6	0.04	-1.47	5.35	43.66	-157.60	681.92	-631.56	34.47	26.49	-0.54	-0.69	0.02	0.01	0.00
ry7	0.05	-0.64	-0.64	21.75	39.54	-631.51	683.18	-153.36	34.39	8.47	-1.10	-0.10	0.03	0.00
ry8	0.00	0.03	-0.24	-0.84	8.23	34.47	-153.30	683.10	-631.15	43.75	16.83	-0.86	-0.05	0.01
ry9	0.00	0.02	0.00	-0.80	-0.43	26.38	34.39	-630.94	684.96	-160.04	45.58	1.62	-0.72	-0.02
ry10	0.00	0.00	0.01	0.01	-0.38	-0.51	8.47	43.39	-159.47	410.36	-332.69	34.02	-2.85	-0.40
ry11	0.00	0.00	0.00	0.02	0.02	-0.69	-1.10	17.08	45.07	-332.63	319.96	-95.90	47.33	1.19
ry12	-0.02	0.00	0.00	0.00	0.01	0.02	-0.11	-1.00	1.87	35.86	-100.62	477.00	-440.28	24.49
ry13	0.02	0.00	0.00	0.00	0.00	0.00	0.04	0.06	-0.90	-4.52	51.53	-438.87	430.20	-34.90
ry14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	-0.02	-0.36	1.16	23.07	-33.66	9.62

(b) Additional horizontal forces at vertical displacement of supports 1 to 14

sens	dy1	dy2	dy3	dy4	dy5	dy6	dy7	dy8	dy9	dy10	dy11	dy12	dy13	dy14
rx1	0.13	-0.72	0.70	0.04	-0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
rx2	-0.62	3.41	-3.07	-0.73	0.93	-0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
rx3	0.57	-2.96	2.46	0.91	-0.82	-0.02	-0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00
rx4	0.04	-0.65	0.81	1.97	-3.05	2.17	-1.25	-0.07	0.08	0.00	0.00	0.00	0.00	0.00
rx5	-0.12	0.98	-0.89	-3.09	4.57	-5.63	4.44	-0.10	-0.27	0.02	0.01	0.00	0.00	0.00
rx6	0.00	-0.07	0.03	2.12	-5.61	23.46	-22.70	3.41	-0.57	-0.10	0.06	0.00	0.00	0.00
rx7	0.00	0.01	-0.05	-1.23	4.45	-22.73	22.85	-6.92	3.90	-0.20	-0.10	0.01	0.00	0.00
rx8	0.00	0.00	0.01	-0.05	-0.12	3.40	-6.94	23.65	-22.83	3.71	-0.89	0.08	-0.03	0.00
rx9	0.00	0.00	0.01	0.07	-0.26	-0.54	3.92	-22.89	22.81	-4.38	1.30	0.08	-0.11	0.00
rx10	0.00	0.00	0.00	0.00	0.02	-0.11	-0.21	3.78	-4.42	1.20	0.08	-1.35	1.05	-0.02
rx11	0.00	0.00	0.00	0.00	0.01	0.05	-0.10	-0.92	1.32	-0.01	-0.65	0.39	-0.08	-0.06
rx12	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.04	-0.71	-0.28	11.65	-11.46	0.96
rx13	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.08	0.45	0.61	-12.02	11.77	-0.98
rx14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	-0.13	1.17	-1.14	0.10

(c) Additional vertical forces at horizontal displacement of supports 1 to 14

sens	dx1	dx2	dx3	dx4	dx5	dx6	dx7	dx8	dx9	dx10	dx11	dx12	dx13	dx14
ry1	-2.56	15.27	-17.02	5.06	-0.62	-0.18	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00
ry2	15.41	-95.23	110.38	-47.75	17.76	0.47	-1.18	-0.04	0.05	0.00	0.00	0.00	0.00	0.00
ry3	-17.22	110.56	-138.25	109.83	-72.89	5.82	2.90	-0.32	-0.15	0.02	0.00	0.00	0.00	0.00
ry4	4.93	-45.01	103.72	-332.69	318.67	-63.65	11.82	2.35	-0.91	-0.13	0.04	0.00	0.00	0.00
ry5	-0.39	14.61	-66.25	316.17	-322.60	123.02	-68.68	1.86	3.42	-0.33	-0.09	0.01	0.00	0.00
ry6	-0.22	0.99	4.60	-61.62	121.44	-429.51	418.44	-66.52	10.30	2.97	-0.95	-0.03	0.02	0.00
ry7	0.04	-1.19	3.22	9.66	-66.63	418.10	-427.09	127.69	-68.24	3.00	1.57	-0.13	-0.03	0.01
ry8	0.01	-0.06	-0.26	2.23	1.96	-66.43	127.65	-429.75	419.91	-69.59	14.32	0.46	-0.43	-0.01

ry9	0.00	0.05	-0.16	-0.81	3.31	10.34	-68.32	420.07	-427.79	98.98	-37.90	1.81	0.49	-0.09
ry10	0.00	0.00	0.01	-0.12	-0.33	3.03	2.92	-70.60	100.45	-118.28	93.15	-17.64	7.42	0.05
ry11	0.00	0.00	0.00	0.04	-0.09	-1.02	1.66	15.37	-39.60	94.08	-81.99	37.86	-27.80	1.39
ry12	-0.02	0.00	0.00	0.00	0.01	-0.02	-0.21	0.27	2.98	-20.67	40.18	-191.90	182.69	-13.07
ry13	0.02	0.00	0.00	0.00	0.00	0.02	0.03	-0.40	-0.36	9.94	-29.65	181.98	-174.49	12.70
ry14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.07	0.00	1.33	-12.41	12.13	-0.97

(d) Additional horizontal forces at horizontal displacement of supports 1 to 14

sens	dx1	dx2	dx3	dx4	dx5	dx6	dx7	dx8	dx9	dx10	dx11	dx12	dx13	dx14
rx1	11.61	-41.96	33.00	-1.39	-1.36	0.06	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
rx2	-42.01	236.28	-247.85	42.22	13.43	-1.67	-0.45	0.04	0.01	0.00	0.00	0.00	0.00	0.00
rx3	33.10	-248.08	316.40	-150.42	45.47	4.60	-1.00	-0.16	0.03	0.01	0.00	0.00	0.00	0.00
rx4	-1.46	42.12	-149.52	551.08	-512.56	56.26	16.21	-1.40	-0.47	0.04	0.01	0.00	0.00	0.00
rx5	-1.36	13.81	44.31	-512.14	575.72	-187.95	61.47	7.55	-1.46	-0.28	0.05	0.00	0.00	0.00
rx6	0.08	-1.81	4.96	55.54	-187.37	807.50	-754.47	54.03	23.36	-1.45	-0.37	0.02	0.00	0.00
rx7	0.04	-0.43	-1.15	16.95	60.82	-754.52	808.63	-190.70	54.35	7.53	-1.48	-0.05	0.02	0.00
rx8	0.00	0.05	-0.17	-1.35	7.51	54.06	-190.76	809.10	-754.36	64.91	11.81	-0.68	-0.11	0.02
rx9	0.00	0.01	0.03	-0.53	-1.44	23.48	54.30	-754.56	810.20	-185.75	53.66	1.27	-0.63	-0.05
rx10	0.00	0.00	0.01	0.04	-0.27	-1.48	7.54	65.35	-186.27	423.14	-338.01	27.05	3.57	-0.66
rx11	0.00	0.00	0.00	0.01	0.05	-0.37	-1.48	11.52	54.08	-338.13	318.69	-72.12	25.16	2.58
rx12	0.01	0.00	0.00	0.00	0.00	0.01	-0.05	-0.60	1.21	26.55	-71.34	333.37	-303.51	14.39
rx13	-0.01	0.00	0.00	0.00	0.00	0.01	0.02	-0.16	-0.62	4.14	24.32	-303.17	300.65	-25.20
rx14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	-0.05	-0.72	2.66	14.31	-25.16	8.93

2.1.3 **Solution of the inverse problem: determination of support misalignment according to change of relative position of journals in the bearing bores.**

The following method allows to control support misalignment continuously and automatically, and to supply values and necessary corrective alignment in the ONLINE mode. At the same time, many other parameters of technical condition of the support system and rotors can be detected. For qualitative solution of this problem, it is necessary to solve a few tasks:

- to provide accurate measurement of shaft neck displacements in the bearing bores within the area of possible displacement, to calculate average values of shaft displacements on the transverse axes of bearings;
- to prepare for each journal bearing: results of calculation of static and dynamic parameters for the purpose of the following interpolation and determination of forces acting in the bearing bore in the known measured position of the shaft neck in the bore, and the shafting stiffness matrix for the support rated position according to calculated loads in supports;
- to calculate vertical and horizontal forces in supports online according to known positions of shaft necks with the help of stiffness factors;
- to signal critical nominal deviation of forces in bearings online;
- to solve the inverse problem online with the help of pre-calculated matrix of stiffness: to determine misalignment of turbine unit rotors according to calculated deviations in supports;

- to calculate stress in rotor journals, welded joints and coupling bolts.

It is important to notice that the required correction of support displacement can be evaluated without a stop of the unit operation, and therefore it may be used for continuous diagnostics of support settlement with a specified time step. And to signal overstress online.

To solve all these problems, it is necessary to overcome numerical instability because of numerical and measuring errors when solving the inverse problem, as well as to develop the procedural framework for application of the obtained results within repair and adjustment works.

Further we will consider the inverse problem solution. Such a problem can be solved with the help of factors of the matrix $[G]$. The vector of position in request of all other supports for the specified position of two any supports can be obtained from (5):

$$\Delta\bar{h}^* = [C^*]^{-1}\Delta\bar{Q}, \qquad (5)$$

where $\Delta\bar{Q}$ is the vector of additional loads in supports to rated ones obtained according to the results of floating-up of the rotor journals by the system COMPACS®. The matrix $[C^*]$ is formed from the matrix $[G]$ factors in view of the fact that the full matrix is a singular one, and it is necessary, within the accuracy to linear and angular spatial attitude of supports in two planes, to build a nondegenerate system of equations. We can receive this solution after exclusion of linearly dependent equations in the initial system. Section 2 presents calculation of misalignment under known deviations of support reaction with application of one iteration. As factors of the stiffness matrix depend on misalignment and support reactions nonlinearly, sometimes we need the second iteration. In case of moderate misalignment only one iteration is necessary in practice.

2.2 Results of calculation of additional reactions of supports in case of operational misalignment of shafting supports **of turbine unit 1000 MW and testing** corrective centering of rotors according to coupling halves.

2.2.1 Direct problem modeling results.

Fig.4 and Table 2 show calculation of supports and support forces in the ideal case when horizontal forces are equal to zero, and support reactions completely balance the rotors weights.

Table 2. Vertical loads in supports for the shaft ideal line, kN

Support No.	1	2	3	4	5	6	7	8	9
Rnom, kN	245.95	221.06	412.6	301.85	831.71	742.13	839.2	741.16	839.2
Support No.	10	11	12	13	14				
Rnom, kN	741.16	1018.8	657.67	132.22	105.11				

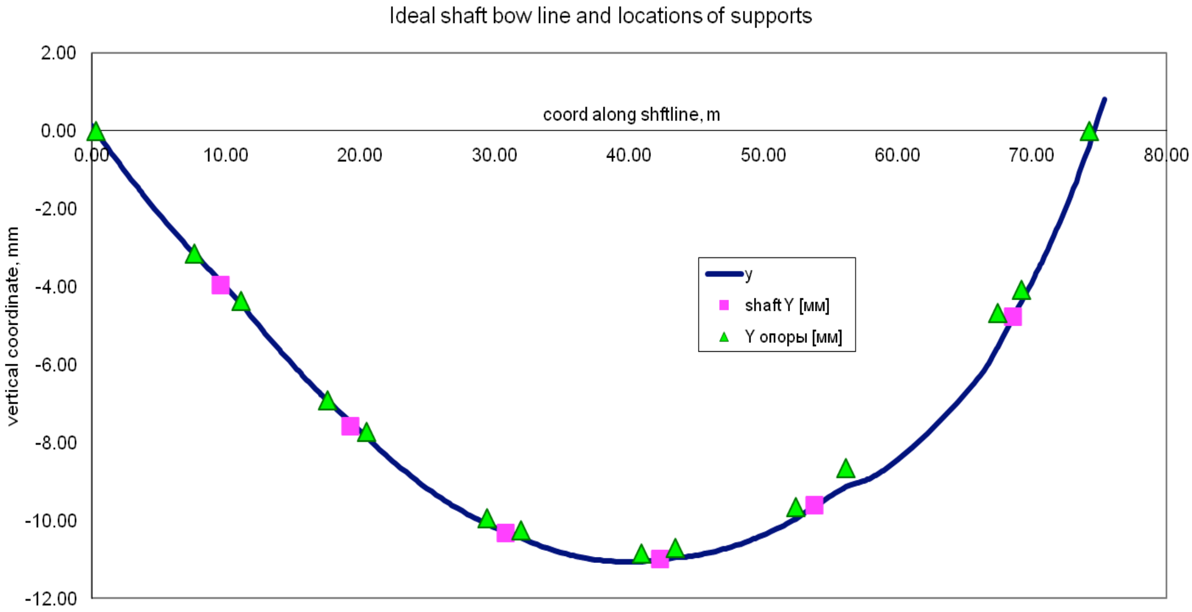

Fig.2. Shafting line (solid blue), positions of horizontal joints of supports (green triangles) and shaft couplings (crimson squares).

1.1.2 Results of the inverse problem modeling.

Tables 3 and 4 show the modeling results for 8 misalignment options and tests of the inverse problem solution. The options cover misalignment of supports in different parts, in vertical and horizontal directions.

It was tested as follows. The ideal support position given in the previous section was used as the base case. Misalignment was introduced on different adjacent supports. For example, for the first 4 options they were used on the second and third supports in accordance with effect upon the coupling half of the high/average pressure rotor. Misalignment values in mm are given in columns of each "test" in Table 3. Every line in the table meets its number of support (1 to 14) and direction of support displacement (x or y). Displacements of the 1st and 14th supports were taken as 0. Test displacement are marked with green in the table. Change of forces on supports were calculated with the help of the model (see Table 4). The influence matrix (see Fig.3) and the vector of force increment in supports were used for calculation of forecast misalignment (inverse problem). The inverse problem solution is shown in the columns “estimate” of proper tests. Cells in blue cover the main components of misalignment.
The test misalignment amplitude did not exceed 0.3 mm in each direction. A forecast error for these tests is within 4.7 % while specifying vertical misalignment, and within 5.7 % for horizontal direction.

Table 3. Tests and results of the inverse problem solution for 8 misalignment options

case	1		2		3		4		5		6		7		8	
	test	estimate	test	estimate	test	estimate	test	estimate	test	estimate	test	estimate	test	estimate	test	estimate
dy2	0	0.001	**-0.15**	**-0.146**	0	-0.014	0	-0.002	0	-0.006	0	-0.001	0	0.001	0	-0.005
dy3	**0.3**	**0.295**	**0.15**	**0.150**	0	-0.006	**0.3**	**0.301**	0	-0.008	0	-0.001	0	0.001	0	-0.007

dy4	0	-0.006	0	-0.001	0	0.000	0	-0.006	0	0.008	**-0.15**	**-0.130**	0	-0.035	0	-0.023
dy5	0	-0.007	0	-0.001	0	0.001	0	-0.008	**0.3**	**0.291**	**0.15**	**0.151**	0	-0.007	**0.3**	**0.292**
dy6	0	-0.008	0	-0.001	0	0.001	0	-0.009	0	-0.015	0	-0.002	0	0.002	0	-0.012
dy7	0	-0.009	0	-0.001	0	0.001	0	-0.009	0	-0.014	0	-0.002	0	0.002	0	-0.013
dy8	0	-0.008	0	-0.001	0	0.001	0	-0.008	0	-0.014	0	-0.001	0	0.002	0	-0.013
dy9	0	-0.008	0	-0.001	0	0.001	0	-0.008	0	-0.014	0	-0.001	0	0.002	0	-0.012
dy10	0	-0.006	0	-0.001	0	0.000	0	-0.007	0	-0.011	0	-0.001	0	0.001	0	-0.010
dy11	0	-0.006	0	-0.001	0	0.000	0	-0.006	0	-0.010	0	-0.001	0	0.001	0	-0.009
dy12	0	-0.002	0	0.000	0	0.000	0	-0.002	0	-0.004	0	0.000	0	0.001	0	-0.004
dy13	0	-0.002	0	0.000	0	0.000	0	-0.002	0	-0.003	0	0.000	0	0.000	0	-0.003
dx2	0	-0.010	0	-0.009	0	-0.004	0	-0.005	0	0.000	0	0.000	0	-0.005	0	-0.005
dx3	0	-0.001	0	-0.001	**0.3**	**0.294**	**0.3**	**0.295**	0	0.000	0	0.000	0	-0.007	0	-0.007
dx4	0	0.000	0	0.000	0	-0.007	0	-0.007	0	-0.014	0	-0.015	0	-0.017	0	-0.013
dx5	0	0.000	0	0.000	0	-0.007	0	-0.007	0	-0.001	0	-0.001	**0.3**	**0.290**	**0.3**	**0.287**
dx6	0	0.000	0	0.000	0	-0.008	0	-0.008	0	0.001	0	0.001	0	-0.013	0	-0.013
dx7	0	0.000	0	0.000	0	-0.008	0	-0.008	0	0.001	0	0.001	0	-0.013	0	-0.013
dx8	0	0.000	0	0.000	0	-0.008	0	-0.008	0	0.001	0	0.001	0	-0.013	0	-0.013
dx9	0	0.000	0	0.000	0	-0.008	0	-0.008	0	0.001	0	0.001	0	-0.012	0	-0.012
dx10	0	0.000	0	0.000	0	-0.006	0	-0.006	0	0.001	0	0.001	0	-0.010	0	-0.010
dx11	0	0.000	0	0.000	0	-0.006	0	-0.006	0	0.000	0	0.000	0	-0.009	0	-0.009
dx12	0	0.000	0	0.000	0	-0.002	0	-0.002	0	0.000	0	0.000	0	-0.004	0	-0.004
dx13	0	0.000	0	0.000	0	-0.002	0	-0.002	0	0.000	0	0.000	0	-0.003	0	-0.003

The obtained values are quite acceptable in practice.
When calculating the shafting line for any position of supports, stress caused by misalignment in rotor necks, welded joints and coupling bolts can be specified. Consideration of these problems goes beyond this article due to its limited volume.
The results if calculation of additional to rated reactions are given in Table 4. The same additional reactions results can be obtained approximately if to multiply the stiffness matrix by the vector of misalignment.

Table 3, in columns “test”, shows the results of the first approximation for calculation of misalignment at the specified (average measured in practice) additional to rated reaction of supports. The test results show that the calculation algorithm for the inverse matrix made from factors of the stiffness matrix works stable. The results of the first approximation for moderate misalignment give good evaluation of misalignment close to the set values.

Table 4. Deviations of forces in supports from rated loads for test misalignment, kN

	1	2	3	4	5	6	7	8
ry1	9.38	10.71	-4.70	4.65	-0.42	-0.03	-0.17	-0.51
ry2	-71.65	-69.81	31.17	-41.06	4.99	-3.25	4.06	8.41
ry3	91.97	81.73	-39.68	53.54	8.91	24.37	-17.82	-6.99
ry4	-42.77	-27.54	30.92	-12.97	-131.22	-136.06	83.79	-55.94
ry5	11.69	3.92	-19.89	-7.78	149.45	139.38	-86.76	71.41
ry6	1.63	1.03	1.37	3.04	-46.24	-28.87	35.92	-11.93
ry7	-0.19	0.01	0.93	0.77	12.32	3.14	-20.39	-8.17
ry8	-0.07	-0.04	-0.08	-0.15	2.46	1.33	0.49	3.10
ry9	0.00	0.00	-0.05	-0.05	-0.14	0.05	0.99	0.86
ry10	0.00	0.00	0.00	0.01	-0.11	-0.06	-0.10	-0.21
ry11	0.00	0.00	0.00	0.00	0.01	0.00	-0.03	-0.02
ry12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ry13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ry14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
rx1	0.58	0.58	9.87	10.20	-0.01	0.00	-0.41	-0.44
rx2	-2.98	-2.98	-74.17	-75.81	-0.36	-0.44	3.81	4.16
rx3	2.91	2.92	94.73	96.25	1.86	2.06	14.68	13.72
rx4	-0.36	-0.21	-45.09	-44.84	-8.02	-8.74	-158.39	-155.19
rx5	-0.13	-0.31	13.60	13.11	7.83	8.42	177.19	174.37
rx6	-0.01	0.01	1.44	1.49	-2.29	-1.80	-56.75	-57.73
rx7	-0.02	-0.01	-0.35	-0.36	1.11	0.53	18.07	19.47
rx8	0.00	0.00	-0.05	-0.05	-0.04	0.00	2.29	2.20
rx9	0.00	0.00	0.01	0.01	-0.07	-0.04	-0.42	-0.51
rx10	0.00	0.00	0.00	0.00	0.01	0.00	-0.08	-0.07
rx11	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
rx12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
rx13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
rx14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The set misalignment is used in each test initially in iteration calculation of the direct problem to receive proper additional reactions. If stiffness was linear from displacements and forces, we would have obtained, when solving the inverse problem, the same misalignment as the set one.

In such a way, for calculation of misalignment in practice, reliable estimate of additional to rated reaction of supports is needed.

3. Conclusions

1. A set of methods for determination of the bearings and shafting technical condition has been developed. The methods are intended to be used in monitoring system COMPACS® for turbine units, including:

A method for determination of support static loads according to the measurement of rotor neck floating-up on oil film is developed.

A method of the inverse problem solution: determination of change of the supports relative position form the ideal mounting line according to the measurement of the rotor necks floating-up on oil film is developed with the help of the shafting stiffness matrix. The suggested methods allow to specify the shafting static line, support misalignment, static properties of oil film of bearings and, finely, stress in shafting elements caused by support misalignment.

2. For a multiple-bearing shafting line of the turbine unit for atomic power stations the shafting stiffness matrix is calculated. With the help of the obtained stiffness matrix we can determine support misalignment when measuring rotor journals floating-up in supports.

3. The stiffness matrix is recommended to be used during adjustment to evaluate effects of changes of supports relative position and rotor alignment correction.

4. The modeling results of the inverse problem solution are given. For the shafting line 1000 MW on 14 supports there are a few test examples given for determination of misalignment according to the specified average deviations in support reactions.

5. The developed methods allow to improve observability of mechanical processes. They are intended for evaluation of the shafting line technical condition and its elements resource in the monitoring systems COMPACS® of SPC DYNAMICS and to prevent sudden failures of equipment while in operation. Moreover, the supposed methods can be used to improve the design calculation and the assurance factors of rotor elements for any units, as well as to monitor and to estimate independently new equipment reliability.

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Session 2A – Condition monitoring systems
Chair: **Professor V Kostyukov** *Room:* **Decouverte 3 and 4**

14.40 [133] Development of methodical support for turbine unit shaft defect and stress monitoring systems at thermal power stations and atomic power stations with the application of shaft displacement sensors

Authors - A I Kumenko, V N Kostyukov, N Y Kuzminykh and A V Timin, Dynamics SPC

It is proposed a modern concept and a set of methods for monitoring of the technical condition of system "turboset's shafting – journal bearings – support units". Technology is developed as an integral part of domestic multipurpose COMPACS® system®. The system input data covers: - design, technological, mounting and operating parameters of the turbine unit; - absolute vibration of supports and control points of the shafting line; - relative displacement and vibration in the rotor journals according to GOST R 55263-2012. Also, the system includes as precomputed: - mounting line of the shafting in cold state; - for each journal bearing, static and dynamic properties of the bearing oil film in domain of possible motion (DPM are given; - static and dynamic properties of supports; - matrix of influence of displacements of supports on the forces in supports of the shafting.
While in operation, the methods allow to determine static and dynamic loads on the supports of turboset, to determine misalignment of supports and to evaluate corrective alignments of the supports and centering of coupling halves. Also, stress in the rotor pins, welded joints and coupling bolts are computed.. We suggest an automatic conclusion on compliance of the technical condition of turboset with safety levels, identification of source of malfunction and recommendations for necessary measures. The work covers some procedures, including ways of determination of stiffness of supports, a method of determination of above mentioned matrix of influence and a method of inverse problem solution – determination of misalignments of the supports based on determination of position of rotor journals in the bearing bores.
We have shown the results of static characteristic modeling by an example of turbine unit 1000 MW for atomic power stations.

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