MODEL BASED DIAGNOSTICS – TODAY AND TOMORROW

Jan KICIŃSKI

Instytut Maszyn Przepływowych PAN, Gdańsk

Summary

The paper presents author's opinions concerning capabilities and limitations of the model based diagnostics. Present development in computer science and methodology of modelling has increased those capabilities considerably. It is obvious that talking about model based diagnostics assumes possessing not only an advanced theoretical model of the examined object but also models of irregular states and mutual relations between defects and their symptoms. Acquiring sufficiently reliable relations of defect-symptom type is a difficult, and frequently an extremely difficult task.

The opinions presented in the paper concern one of the most intriguing phenomena, namely the formation of whirls and whips in slide bearings of a rotating machine. Although those phenomena are being the object of investigation in many research centres all over the world, their physics has not been satisfactorily recognised yet. The paper presents the abilities of computer simulation of the development of oil whirls and whips using the methods characteristic for model based diagnostics. The presented opinions are only considered an example of capabilities of this line of science. Moreover, they were used for formulating conclusions of more general nature.

Keywords: model-based diagnostics, oil whirl and whip, hydrodynamic instability, rotor dynamics

Streszczenie

W referacie przedstawione zostały rozważania autora dotyczące diagnostyki według modelu, jej ograniczeń i możliwości. Współczesny rozwój informatyki a także metodologii modelowania znacząco te możliwości zwiększył. Jest rzeczą oczywistą, iż aby mówić o diagnostyce według modelu dysponować musimy nie tylko zaawansowanym modelem teoretycznym analizowanego obiektu, ale także modelami stanów anormalnych i wzajemnymi relacjami pomiędzy defektami i ich symptomami. Zdobycie odpowiednio wiarygodnych relacji typu defekt-symptom jest zagadnieniem trudnym , a często bardzo trudnym.

Przedstawione w niniejszej pracy rozważania odnoszą się do jednego z najbardziej frapujących zjawisk, a mianowicie rozwoju wirów i bicia olejowego w łożyskach ślizgowych maszyny wirnikowej. Pomimo, iż zjawiska te były i są nadal przedmiotem badań w wielu ośrodkach na całym świecie, fizyka tego zjawiska nie została wyczerpująco rozpoznana. Przedstawione zostaną możliwości komputerowej symulacji rozwoju wirów i bicia olejowego za pomocą metod właściwych diagnostyce według modelu. Przedstawione w pracy rozważania potraktowane zostały wyłącznie jako przykład możliwości tej dyscypliny wiedzy i posłużyły do sformułowania bardziej ogólnych wniosków.

1. INTRODUCTORY REMARKS

A basic problem of the model based diagnostics is the ambiguity of relations between modelled defects and their symptoms. This fact makes the interpretation of the results obtained from the computer analysis considerably more difficult. When examining, for instance, a big rotating machine, i.e. the object of extreme complexity, we have to deal not only with the ambiguity of the defect-symptom type relations, but also with problems in modelling numerous phenomena, like material or external damping, shape of the kinetostatic line, stiffness and dynamic damping of the supports, or, last but not least, the development of hydrodynamic instability in sliding bearings, in particular the development of oil whirls and whips. A classical approach to this type of objects is shown in Fig. 1.

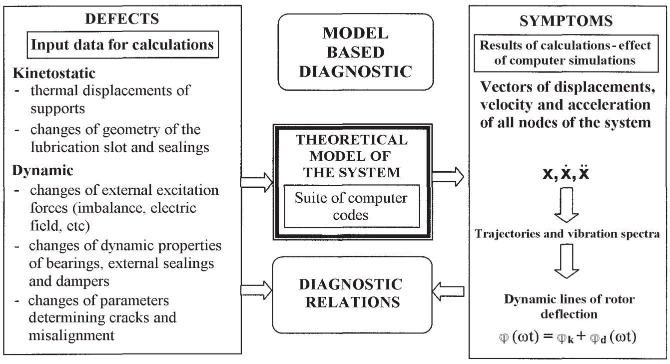

Fig. 1. Model based diagnostics of rotating machinery. A concept of acquiring diagnostic relations.

2. RESEARCH TOOLS AND VERIFICATION

In a classical rotating machine three principal sub-systems can be named:

- rotor line with discs, clutches and imperfections like cracks or misalignments
- hydrodynamic journal bearings and labyrinth seals
- foundations with supports and external bearing fixings

Particularly difficult for theoretical modelling are slide bearings and labirynth seals. In IFFM PAS, Gdansk, a so called diathermal model of heat transfer in bearings (the code DIATER) has been developed, which consists of coupled Reynolds, energy and conduction equations, and a corresponding model of hybrid lubrication in the case of supplying from the siphon pockets and possible bush skewness (the code IZOSLEW) – Fig. 2.

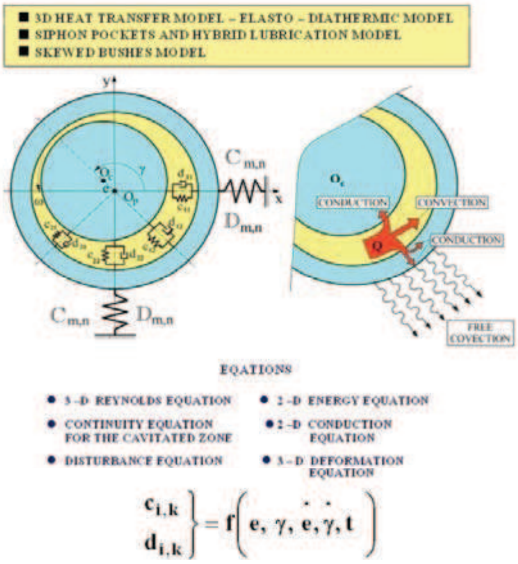

Fig.2. Thermal model of bearing assumed in analysis (DIATER) and corresponding hybrid lubrication model (IZOSLEW*)*

The above bearing models have been described in detail in [23] or partially in [22,24,25] and hence are not presented here.

The line of rotors with discs has been modelled by means of the FEM method featuring typical beam elements with 6 degrees of freedom in each node [16,17,22].

A key issue is now to develop a general algorithm of calculations, both kinetostatic and dynamic, which would combine all mentioned above sub-systems of the entire system, and the algorithm of dynamic calculations incorporating possible non-linear external excitations of the system and large displacements of shafts in bearings. In IFFM PAS, Gdansk, a computer system named **NLDW** has been developed for non-linear analysis of very complex rotor-bearing-foundation systems. The system NLDW forms a basic research tool used in the present work. Due to obvious reasons, the issues concerned with capabilities of that vast system will not be discussed here, nor the details related to the description of the utilized equations and simplifying assumptions. Such information can be found in [18-20,22,24,25].

Fig. 3. Multi-scale research rig used for experimental verification of NLDW system. The object assumed in further investigations.

A separate issue is the experimental verification of the developed research tools. The NLDW system has undergone a detailed verification procedure both in the laboratory scale and on real objects, such as large power industrial turbine units. Two examples of code verification on the research rig will be presented, whilst neglected will be abundant reports on the code verification on real objects. Fig. 3 presents a photograph of a multi-scale and multi-support research rig operating at the IFFM PAS vibroacoustics laboratory, where the verification investigations have been conducted. The next figure, Fig. 4, shows an example of NLDW code verification under typical stable conditions of the rig operation, whereas in Fig. 5 a more interesting case of verification is given, after the stability threshold has been surpassed, which resulted in the existence of oil whirls. This is of high importance as the modelling of oil whirls under conditions of stability loss in a large rotating machine is very difficult. Therefore the results presented in Figs. 4 and 5 can be regarded as satisfactory.

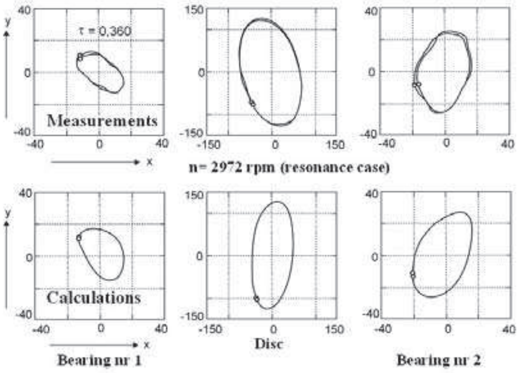

Fig. 4. Example of verification of NLDW system on the multi-scale research rig within the range of its stable operation (in resonance)

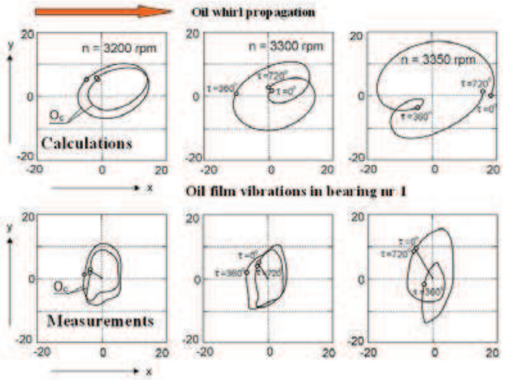

Fig. 5. Example of verification of NLDW system on the multi-scale research rig after surpassing the stability threshold (in the region of oil whirls)

3. SELECTED SIMULATION TESTS. DEVELOPMENT OF OIL WHIRLS AND WHIPS

The example of verification of the NLDW computer system, shown in Fig. 5, refers to the experimental measurements and computer simulation of oil whirls in the slide bearing mounted at the research rig. It has been well recognised that oil whirls form when the system surpasses the stability threshold, i.e. in the range in which traditional methods of linear modelling of the phenomenon cannot be used any longer. It can be shown that in those cases a non-linear model relatively well describes the state of a machine, as it allows analysing qualitative transitions, in this particular case from classical vibrations with elliptical trajectory shapes to those with whirl structures. The detailed computer analysis makes it also possible to recognise characteristic diagnostic factors of the current state of the examined phenomenon and understand its physics. Without simulation studies such an assessment, based solely on experimental results, would be more difficult and, first of all, much more expensive.

So, let us carry out a bit more systematic study of the propagation of oil whirls, which, however, will be treated here only as an illustrative example of capabilities of the model based diagnostics. Fig. 6 shows an object selected for investigations (a two-support model rotating machine with slide bearings), along with the MES digitisation and node numbers. We can observe the development of oil whirls and whips in bearing No. 1 as a function of the increment of rotor rotational speed after the stability threshold has been surpassed. The system is subject to action of external excitation forces resulting from residual unbalance of the disc. Basic characteristics of the bearings are the following: journal diameter – 0.1 m, radial cylindrical clearance - 90 μm, bushing width / journal diameter ratio - 0.5, lubricating agent – machine oil Z-26. The results of the computer simulation carried out using the NLDW system are given in Figs. 7-9.

An interesting conclusion resulting from Fig. 7 is that oil whirls develop by slow splitting of the elliptical trajectory into two loops: external and internal. In the first phase the internal loop decreases, then starts increasing again, during which it moves to the place previously occupied by the external loop. The initial external loop decays with time, and in the final whirl development phase we have only one trajectory of a shape close to a circle. The whirls start the next, much more dangerous development phase, which is oil whipping. This situation is illustrated in Fig. 8. The observation of phase markers, i.e. the locations on the trajectories corresponding to external excitation force vectors directed horizontally to the right in the assumed reference system (TAL=0, 360, or 720 degrees) provides practical data on the diagnostic factor referring to the hydrodynamic instability, as illustrated in Figs. 9 and 10.

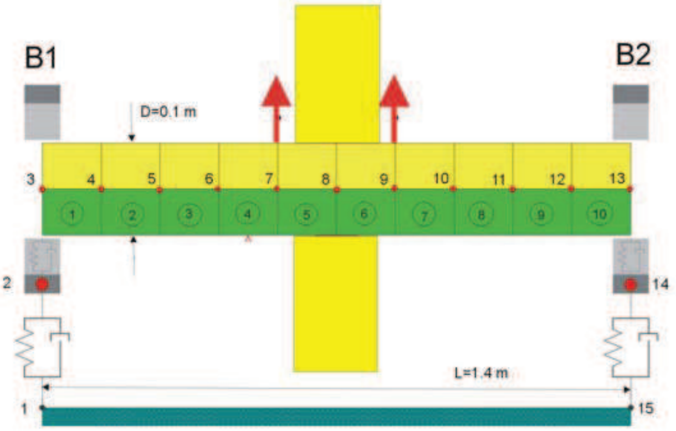

Fig.6. The object used for investigations, (two-support model rotating machine with slide bearings), along with MES digitisation and node numbers.

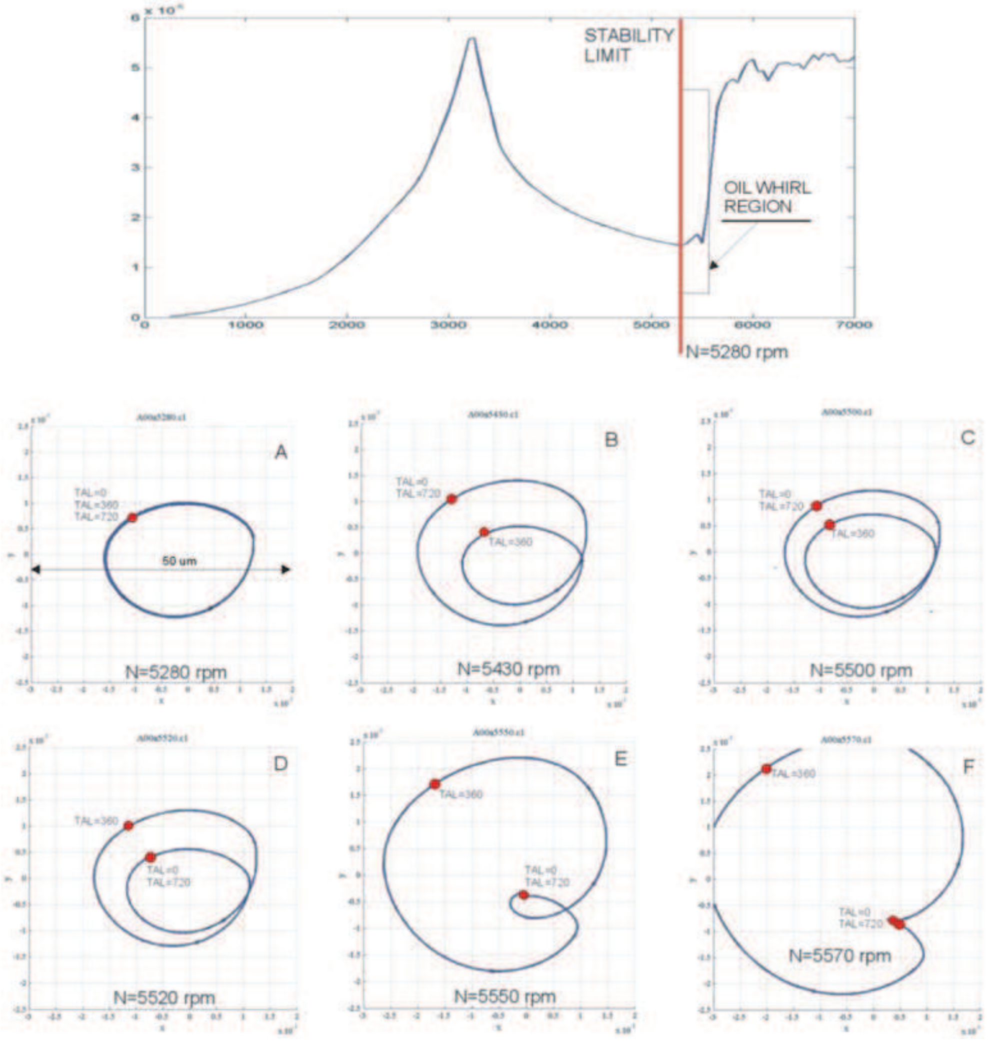

Fig.7. Computer simulation of development of oil whirls after surpassing the stability threshold of the system – phase of small oil vibrations. Calculations were carried out using NLDW system

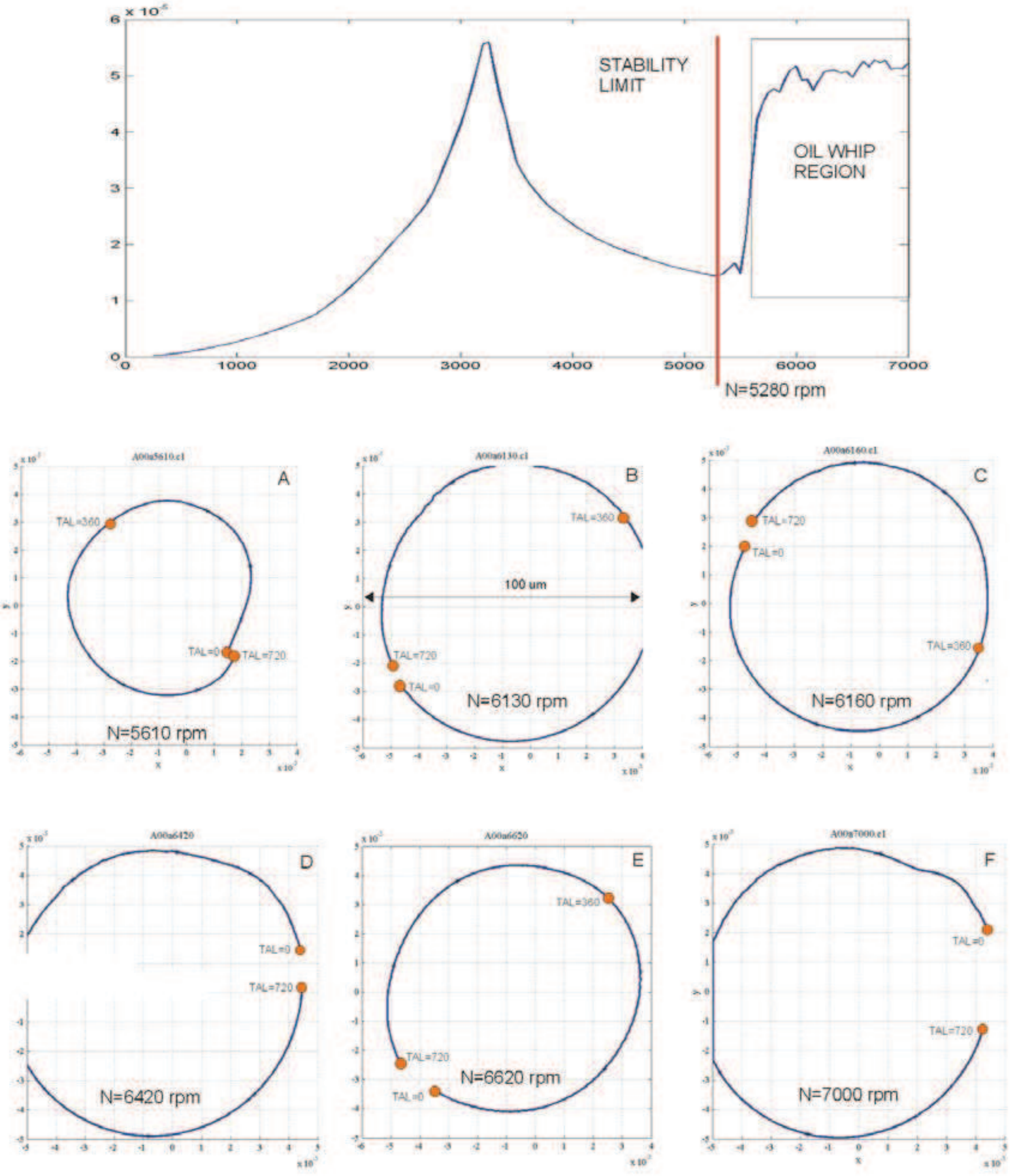

Fig. 8. Simulation of the transition of oil whirls to the oil whipping phase. Highly developed hydrodynamic instability – strong and dangerous oil vibrations.

Fig. 9 shows that in advanced phases of oil whipping the same position of the external excitation force vector (unbalance vector) corresponds to three different pressure distributions and, as a consequence, three different dynamic states of the bearing. It means that this state is represented by as many as three phase markers in the recorded trajectory range between 0 and 720 degrees. In this convention the oil whirls have two phase markers, while the range of stable operation of the machine – one marker. This is illustrated in Fig. 10. The conclusions resulting from the analysis of Fig. 10 can be of high importance for monitoring the hydrodynamic instability, as they deliver practical measure of this type of states in the form of a number of phase markers. Obviously, other diagnostic determinants can be named which are specific for oil whirls and whips (vibration spectra, for instance), but they are neglected here due to limited volume of the paper and its aim.

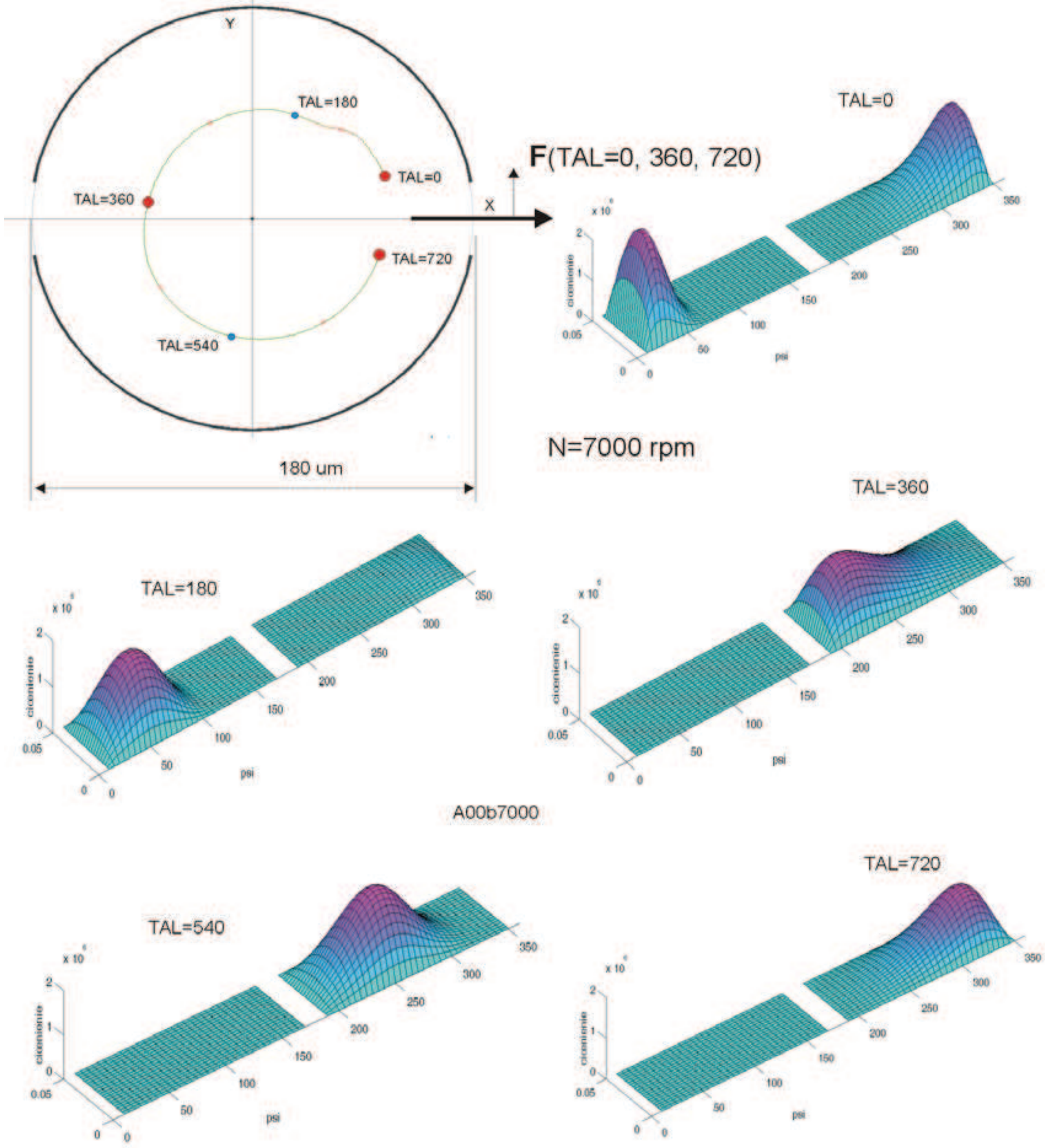

Fig. 9. Instantaneous hydrodynamic pressure distributions in the bearing for selected journal positions on the trajectory within the oil whipping range. The trajectory is presented on the background of the bearing clearance circle.

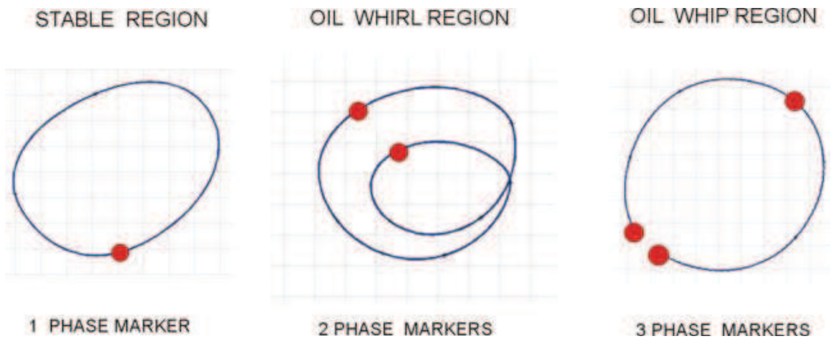

Fig. 10. Proposed classification of hydrodynamic instabilities in the system and introduction of diagnostic determinants.

4. FINAL CONCLUSIONS

The examples of whirl propagation and oil whipping which are given in the paper make only a small part of research activities in this area. But even in this limited form they prove interesting capabilities of the computer analysis, increasing the potential of the new and rapidly developing branch of science which is the model based diagnostics. Numerous similar advanced analyses of regular and irregular states of various types of objects are expected to take place in the future, thus defining future directions of research development in technical diagnostics. This fact will affect current challenging tasks not only in diagnostics, but also in the entire science oriented on the construction and operation of machines.

REFERENCES

1. Dan Guo, Fu-Lei Chu, Yong-yong He, *Vibration analysis of rotor with transverse surface cracks*, Proceedings of ASME Turbo Expo 2003, June 16-19, 2003, Atlanta, USA, GT2003-38041.
2. Itzhak Green, Cody Casey, *Crack detection in rotor dynamic system by vibration monitoring*, Proceedings of ASME Turbo Expo 2003, June 16-19, 2003, Atlanta, USA, GT2003-38659.
3. Ilmar F. Santos, Rodrigo Nicoletti, A. Scalabrin, *Feasibility of applying active lubrication to reduce vibration in industrial compressors*, Proceedings of ASME Turbo Expo 2003, June 16-19, 2003, Atlanta, USA, GT2003-38225.
4. J. Gomez-Mancilla, V.R. Nosov, R. Garcia-Illescas, *Detection of steady crack growth on rotating shafts*, ISCORMA-2, Gdansk, Poland, 4-8 August 2003.
5. J. T. Sawicki, D. E. Bently, Xi Wu, G. Y. Baaklini, M. I. Friswell, *Dynamic behavior of cracked flexible rotor subjected to constant driving torque*, ISCORMA-2, Gdansk, Poland, 4-8 August 2003.
6. N. Bachschmid, E. Tanzi, *Non-linear effects in cracked rotors*, IFToMM Conference, Sydney, 2002.
7. N. Bachschmid, P. Pennacchi, E. Tanzi, P. Verrier, F. Hasnaoui, K. Aabadi, *Crack detectability in vertical axis cooling pumps during operation*, IFToMM Conference, Sydney, 2002.
8. J.D. Yang, T.S. Zheng, W. Zhang, H.Q. Yuan, B.C. Wen, *The complicated response of a simple rotor with a fatigue crack*, IFToMM Conference, Sydney, 2002.
9. R. Garcia-Illescas, J. Gomez-Mancilla, *Vibration analysis in the characterization of the dynamic behavior of cracked rotating shafts*, IFToMM Conference, Sydney, 2002.
10. SSubbiah, J. Montgomery, R.L. Banks, *Studies on rotor cracks due to bending and torsional effects*, IFToMM Conference, Sydney, 2002.
11. A. K. Darpe, A. Chawla, K. Gupta, *Analysis of the response of a cracked Jeffcott rotor to axial excitation*, Journal of Sound and Vibration, 2002, **249**, pp. 429-445.
12. C. A. Papadopoulos, A. D. Dimarogonas, *Coupled longitudinal and bending vibrations of a rotating shaft with an open crack*, Journal of Sound and Vibration, 1987, **117**, pp. 81-93.
13. A. Muszynska, P. Goldman, D. E. Bently, *Torsional/lateral vibration cross-coupled responses due to shaft anisotropy: a new tool in shaft crack detection*, ImechE, 1992, C432/090, pp.257-262.
14. M.–W. Suh, M.–B. Shim, M.–Y. Kim, *Crack identification using hybrid neuro- genetic technique*, Journal of Sound and Vibration (2000) **238**(4), pp. 617-635.
15. A. Nandi, S. Neogy, *Dynamic response of cracked beams and beams with an imperfect support*, Proceedings of VETOMAC-1 Conference, Bangalore, INDIA, 2000.
16. W. Ostachowicz, M. Krawczuk, *Coupled torsional and bending vibrations of a rotor with an open crack*, Ingenieur-Archiv, 1992, 62, pp. 191-201.
17. J. F. Knott, *Fundamentals of fracture mechanics*, Butterworths, London, 1973.
18. J. Kiciński, R. Drozdowski, P. Materny, *The nonlinear analysis of the effect of support construction properties on the dynamic properties of multi-support rotor systems*, Journal of Sound & Vibration (1997) **206**(4), pp. 523-539.
19. J. Kiciński, R. Drozdowski, P. Materny, *Nonlinear Model of Vibrations in a Rotor – Bearings System*, Journal of Vibration & Control, Vol. 4, n. 5, 1998, pp. 519-540.
20. J. Kiciński, A. Markiewicz–Kicińska, *Coupled nonlinear vibrations in multi-support rotors founded on slide bearing*, Proceedings of VETOMAC-1 Conference, Bangalore, INDIA, 2000, pos. CP 047.
21. J. Kiciński, W. Cholewa, *Diagnostic system DT200-1 for large power (200 MW) turbosets*, 1998, IFFM Proceedings, Gdansk, Poland.
22. Z. Walczyk, J. Kiciński, *Dynamics of Turbosets* (monograph in polish), Technical University of Gdansk Publishers, Gdansk, 2001.
23. J. Kiciński, *Theory and investigations of hydrodynamic journal bearings* (monograph in polish), Ossolineum Publishers, Wrocław-Warszawa-Kraków, 1994.
24. J. Kiciński, *Coupled Non-Linear Vibrations in 200* MW Turbosets, IFToMM Sixth International Conference on Rotor Dynamics-Proceedings, Vol. 1/2002, pp. 520-530.
25. J. Kiciński, A. Markiewicz–Kicińska, *Coupled Non-Linear Vibrations in Multi- Supported*

Rotors Founded on Slide Bearings, Advances in Vibration Engineering, Vol. 1, No 2, The Scientific Journal of the Vibration Institute of India, pp. 141-152.

Jan KICINSKI, born 1948, Professor, Deputy Director of the Institute, Head of Department of Rotor Dynamics and Jour-nal Bearings, 1972- M.Sc. from Faculty of Mechanical Eng. TU Gdansk, since 1972 employed at Institute of Fluid-Flow Machinery (IFFM), 1986 - D.Sc. from IFFM, since 1995 full Professor. Since 1995 - Coordinator of two large Government ordered Research Projects concerning diagnostics of large power objects. Person in charge of Centre of Excellence. The main field of his research is in model-based diagnostics with special emphasis on the dynamics of rotors and journal bearings, coupled non-linear vibrations and new diagnostic determinants and inverse models methodology for knowledge acquisition. He has worked in his field of expertise for 20 years. He leads a research group of 16 staff. He has published over 100 scientific papers in journals and conferences and is on the editorial bord of three scientific journals. 1998 he has been awarded with Siemens Research Prize.