Model Based Diagnostics – Today and Tomorrow

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Abstract- 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 centers all over the world, their physics has not been satisfactorily recognized 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. Another very interesting issue is an assessment of the influence of a random character of certain input data – in this case – changes of external excitations of the system. This problem is related to the so-called heuristic models often placed in opposition to widely used algorithmic models. The main issue concerned the question whether the heuristic methodology can move to the techniques, in this case, the rotor dynamics. Heuristic approach may be the future of model based diagnostics.

The objects of investigations were the high-speed rotor of a micro turbine being an element of the micro power plant in dispersed power engineering based on renewable energy sources.

In both cases (whirls and heuristics), it is necessary to have very powerful tools for analyzing the behavior of objects, especially in the non-linear range. These tools are the basis of modern model based diagnostics.

Keywords- Model-Based Diagnostic; Oil Whirl and Whip; Hydrodynamic Instability; Rotor Dynamics; Nonlinear Vibrations; Heuristic Problems

I. 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. In the model based diagnostics plays a key role a research tools like theoretical models and computer codes. Now we will present such tools (system MESWIR) developed at the Institute of Fluid Flow Machinery Polish Academy of Sciences (IFFM PAS) in Gdańsk.

II. RESEARCH TOOLS AND THEIR VERIFICATION

The MESWIR computer code, based on nonlinear models of complex systems rotor-bearings, was applied in research. Theoretical models, basic equations as well as the system itself have been presented already several times during the conferences and in publications [1, 2, 3]. Due to that and having in mind the paper space limitation and its different aims, the MESWIR series code will not be presented here in details. For the purposes of this paper we present only a block diagram of computing systems MESWIR – Fig. 2. However, it is worth mentioning that the most useful feature of this system is the possibility of description of the rotor machine state both in a linear and nonlinear range by means of the same tool, thereby describing new vibration forms at transition of the stability limit. The MESWIR code was experimentally verified both at the research stand and with using real systems such as large power turbo-sets – Figs. 3, 4, 5 [1].
Fig. 2 Block diagram of computer program MESWIR. The set of differential equations [1].

Fig. 3 Experimental verification on real objects of the computer program MESWIR. At the top: photo of 200 MW turbine-set, bottom: sample journal displacements in the bearing [1].

Fig. 4 Sample results of the program MESWIR verification on the real 200 MW turbines set shown in Figure 3.
In the case of large object we can see (Figs. 3, 4) only one example of model tuning procedure performed on real 200 MW Turboset and the measurements results and calculation results in the form of so called diagnostic cards, that means in the form of setting-up absolute vibration velocity and relative shaft displacement for all 7 bearings. Taking into account that we have to deal with so complicated object, the agreement between experiment and theory we can recognize as qualitative and thereby as satisfactory (Fig. 4).

One examples of code verification on the research rig will be presented in Fig. 5. Fig. 5 (left) presents a photograph of a multi-scale and multi-support research rig operating at the IFFM PAS vibroacoustics laboratory, where the verification have been conducted. Fig. 5 (right) presents an interesting case of verification, namely a situation where the stability threshold has been surpassed. This case 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 Fig. 5 can be regarded as satisfactory.

III. EXAMPLE OF THE POSSIBILITIES OF MODEL BASED DIAGNOSTICS, DEVELOPMENT OF OIL WHIRLS AND WHIPS

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. Let us assume the object of investigations shown in Fig. 5. Basic characteristics of the bearings are the following: journal diameter – 0.1 m, radial cylindrical clearance - 90 \( \mu \)m, bushing width / journal diameter ratio - 0.5, lubricating agent – machine oil Z-26.

The results of the computer simulation carried out using the MESWIR system are given in Figs. 6 – 8. 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.
Fig. 6 Computer simulation of development of oil whirls after surpassing the stability threshold of the system – phase of small oil vibrations (upper), oil whipping phase - highly developed hydrodynamic instability (lower) 

Calculations were carried out using MESWIR system.
Fig. 7 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. 8 Proposed classification of hydrodynamic instabilities in the system and introduction of diagnostic determinants.
An interesting conclusion resulting from Fig. 6 (upper) 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. 6 (lower). 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. 7 and 8.

Fig. 7 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 have one marker. This is illustrated in Fig. 8. The conclusions resulting from the analysis of Fig. 8 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.

IV. HEURISTIC APPROACH - THE FUTURE OF DIAGNOSTICS?

A classic, traditionally applied for many years, approach to the state modeling of various kinds of machines is the algorithmic approach, i.e. the one in which for the known set of input data we obtain the same, precisely repeatable, set of output data (results). This is the obvious consequence of calculation capability of computers and the applied programs. However, this type of ‘traditional’ research tools, often highly advanced and applicable in practice, are neither able to correct the already introduced data nor to modify the assumed model depending on external conditions during the calculation procedure being in progress.

Meanwhile natural phenomena and a human nature (and thereby objects created by it) are of a heuristic character, which means possible feedbacks occurring in processes, intrinsic data and the previously assumed methodology of state assessment corrections. It also means the necessity of taking into account influences of various errors and the uncertainty of input data, what is often intuitively done – Fig. 9.

Why the introduction of heuristic methodology for rotor dynamics can be fruitful? Because the two reasons are very important here:
- the possible work in unstable region – the need of model auto-corrections;
- stochastic variability of input data, random excitations.

In both cases there is no formal proof of correctness. Despite of this we have to find the acceptable solution – Fig. 10.
It is worth to mention that the trial of heuristic modeling means the necessity of having highly advanced ‘traditional’ research tools. The so called nonlinear description is extremely important since heuristic models are nonlinear by nature. Another substantial feature is the possibility of a smooth transition from the linear to nonlinear description applying the same research tools (the superposition principle cannot be used in this case). In consideration of the above, the MESWIR series code was applied in investigations because it meets these conditions.

A. Object of Investigation - Micro Turbines

Problems related to ecological energy generation at a small and dispersed scale have become very important in recent years. A dispersed power engineering requires building micro power plants which means also micro turbines of electric power close to a few KW. The idea of building micro turbines for low-boiling agents ORC, which ensures small dimensions of devices and easiness of servicing, has become attractive. The main problem becomes ensuring the stable operation of the device within the entire rotational speed range of the rotor. This type of devices are most often coupled with boilers supplied with renewable energy sources. A concept of such micro turbines (3 KW Power) developed in the IFFM PAS in Gdansk is shown in Fig. 11. For the lubrication purposes we can take the lubricant from the liquid phase and then we should use hydrodynamic journal bearings (classical or foil bearings) or we can take the lubricant from steam phase and then we can use only the gas bearings.

B. Example of Investigation – Randomly Changing Excitation Force Vector

Fig. 12 presents the concept of random changes of external excitation forces acting on a bearing and rotor disc. The randomness of changes was assumed (random-number generator was applied) although within limits +/-δP in proportion to the basic value P. Calculations were performed for different δP values simulating in this way various possible situations (e.g.: displacement of rotating masses, influence of magnetic fields, etc.).
The calculation results for the rotor shaft rotational speed from 300 rpm to 5550 rpm are shown in Figs. 13 and 14. The trajectory of the rotor centre loaded by a constant force (basic) – rotating synchronously – is shown for the comparison on the left-hand side of each figure, whereas the trajectory of the rotor loaded by randomly changing force – within limits \( \pm \delta P = 20\% \) in proportion to the basic force \( P \) – is shown on the right-hand side of the figure. Images of trajectories in coordinate systems related to the maximum value of bearing clearance are placed in the upper part, while images of trajectories magnified as much as possible to exhibit clearly the phenomena are shown in the lower part of the figure.

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**Fig. 12** Concept of random changes of external excitation forces acting on a bearing and rotor disc. From left: traditional calculation, calculation with randomly changing vector for relative bearings and disc vibrations.

**Fig. 13** Displacement trajectories of the rotor centre – within a stable operation range – calculated for the constant excitation force (basic) \( P \) (part A) and for the randomly changing – within limits \( \pm \Delta P = 20\% \) (part B) shown at the background of the rotor amplitude-frequency response.
The analysis of the figure indicates that influence of randomly changing values of the external excitation force is significant in the case of small rotational speed of the rotor. When the speed increases, this influence diminishes, what can be explained by the influence of rotor inertial forces generally attenuating a time-history. However, disturbances caused by the stochastic variability of input data decay when the rotor rotational speed increases, it means when the hydrodynamic instability develops (Fig. 14). This is rather a startling result, since it could have been expected that such perturbations – after exceeding the stability limit – would intensify the instability of the entire system since it has been already unstable. Similar conclusions were found when investigations were performed for various $\delta P$ values and various algorithms of random excitations. Thus, a system defect in the form of the hydrodynamic instability attenuates to a certain degree the defect caused by stochastic effects of input data. It is an interesting observation resulting from the performed research.

V. CONCLUSION

The examples of whirl propagation, oil whipping and preliminary considerations concerning heuristic modeling of rotors 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