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INSTITUTE OF FLUID-FLOW MACHINERY
POLISH ACADEMY OF SCIENCES



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## 113

**Selected papers from the International Conference on *Turbines of Large Output* devoted to 100th Anniversary of Prof. Robert Szewalski Birthday, Gdańsk, September 22-24, 2003**

WYDAWNICTWO IMP PAN

GDAŃSK 2003

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*Transactions of the Institute of Fluid-Flow Machinery* have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
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The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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No. 113, 2003, 3-4

# Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{th}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

*Prof. Jarosław Mikielewicz*
Editor-in-Chief

*Dr Edward Śliwicki*
Managing Editor

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 113, 2003, 51-66

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# Monitoring and diagnostic system for high power turbine units

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## Abstract

The paper presents new design of monitoring and diagnostic system for steam turbine unit. The system is designed as modular and can be relatively easy extended with new hardware and software modules. The system has distributed architecture based on computer network concept and is designed as multi-user and multitasking that many users have access to diagnostic information simultaneously. The system is equipped with high end expert system based on artificial intelligent algorithms. Performance has been tested on 200 MW turbine unit and it operates successfully at Kozienice power plant for longer then 5 years.

**Keywords:** Diagnostic and monitoring system; Expert system; Vibrodiagnostics; Software for diagnostic systems.

## 1 Introduction

Described below monitoring and diagnostic system DT200-1 has been designed for the KBN project managed by the Institute of Fluid Flow Machinery PAN during a period from 1995 till 1997. The system has been designed for particular turbine units for carbon coal fuel with power of 200 MW that are most popular in Poland [1].

Design team included several subteams which realized separate project tasks.

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Institute of Fluid Flow Machinery PAN (Prof. Kiciński team) managed the project and did research related to software for simulation of dynamic behavior of turbine unit and its verification on experimental rig. The simulation results helped to find diagnostic symptoms for particular failures. Silesian University of Technology (Prof. Cholewa team) was the main designer of system concept and software implementation. Their research included design of dynamic expert system. Institute of Thermal Machinery Technical University of Czestochowa (Prof. Drobniak team) took a part in hardware design and testing as well as in GUI and prognostic software implementation. Silesian University of Technology (Prof. Kosman team) prepared algorithms for thermal stress and efficiency assessment. Institute of Power Engineering in Warsaw (Prof. Orłowski team) based on experimental study of many different turbines units supplied alarm and alert criteria for the system. Poznań University of Technology (prof. Cempel team) designed a subsystem for fans, pumps and blowers monitoring and diagnostics, which has been tested in Karolin EC in Poznan. Prof. Uhl team (Energocontrol) designed and manufactured subsystem for data acquisition and processing including hardware and real time software. The system is in use from 1997 at Kozienice Power Plant. During this period system has been updated and developed according to new available hardware and software solutions. The system can be relatively easy adapted to any steam turbine unit.

# 2 System idea and hardware solutions

System DT200 -1 consists of three main layers:

- hardware and low level software layer,
- high level software layer,
- simulation software layer

The main element of system hardware is processor station which is responsible for data acquisition and signal processing. The station is built based on industrial computer with extra high specialized boards and real time operating system. High level software includes system management, communication, analytical and user interfaces software which is implemented under MS Windows operating system. Simulation software is independent software and procedures for helping to build diagnostic data base with unified format. This data base is very helpful to assess turbine unit failures. There are three main features of the system functionality which distinguish the system from different existing solutions. The system is fully open by means of possibilities to connect to standard computer hardware and new software modules can be easily build, because system is equipped with standardized hardware and software interfaces. A dynamic expert system is build in to the system architecture in proposed system design, this is a unique solution not existing in other types of diagnostic system. The system is designed to fulfill the requirements of centralized diagnostic center which can offer services for many different power plants installations world wide.

The system has typical hierarchical open architecture characterized by independent but cooperating modules. Structure of the system and main modules are shown diagrammatically in Fig. 1.

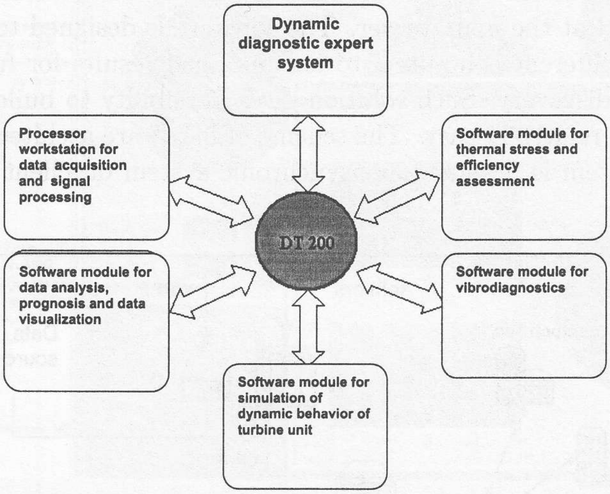


Figure 1. Scheme of DT200 system architecture.

Diagnostic knowledge is represented in the system in a form of:

- Diagnostic models of steam turbine unit.
- Simulation model for system dynamics (rotor shaft line).
- Thermal stress model.
- Adaptive models for observed diagnostic signals.
- Catalogues with diagnostic relations.
- Set of limits value for given diagnostic symptom.

System DT200 is a first Polish high level monitoring system with expert system implemented and included artificial intelligence based algorithm which is operating in industrial environment.

In the system two main parts should be distinguished; processor workstation and operator workstation. Such architecture is typical for currently design monitoring systems [2].

Processor workstation tasks are the following: management of measurements (e.g. vibration measurements), on-line signal processing and storing results in data buffer. The processor module is working as server and has multitasking and multi-user functionality and is implemented uder real-time operating system VxWorks®. The system server is connected to other data sources employing TCP/IP protocol which is also available in turbine unit control system (WDPF in existing installation). The operator workstation software modules can run on different computers and different modules separately but data are available from database located at the main server. The software is designed to permit cooperation of many different computers to use obtained results for future simulation and knowledge discovery. Such solution gives possibility to build diagnostic systems extensions relatively easy. The scheme of hardware architecture is shown in Fig. 2. The system is designed as asynchronic system on client level which is a

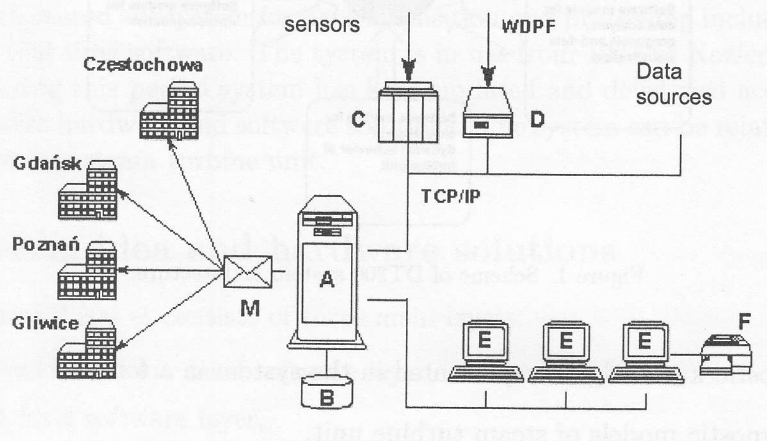


Figure 2. Scheme of hardware architecture. A – system server, B – database, C – processor workstation, D – interface to control system, E – clients, users, system administrator, F – other diagnostic system, M – modem for external communication.

reason for non on-line operation of all users and system performance depends on the number of login users at the same time.

But the processor workstation operates in synchronous mode that data available in database are on-line and are synchronic data.

User software modules are implemented in MS Windows NT. Graphical User Interface in the system is based on windows which can be chosen from task three and system recourses. The user can open several software modules simultaneously. Typical view of GUI window is shown in Fig. 3.

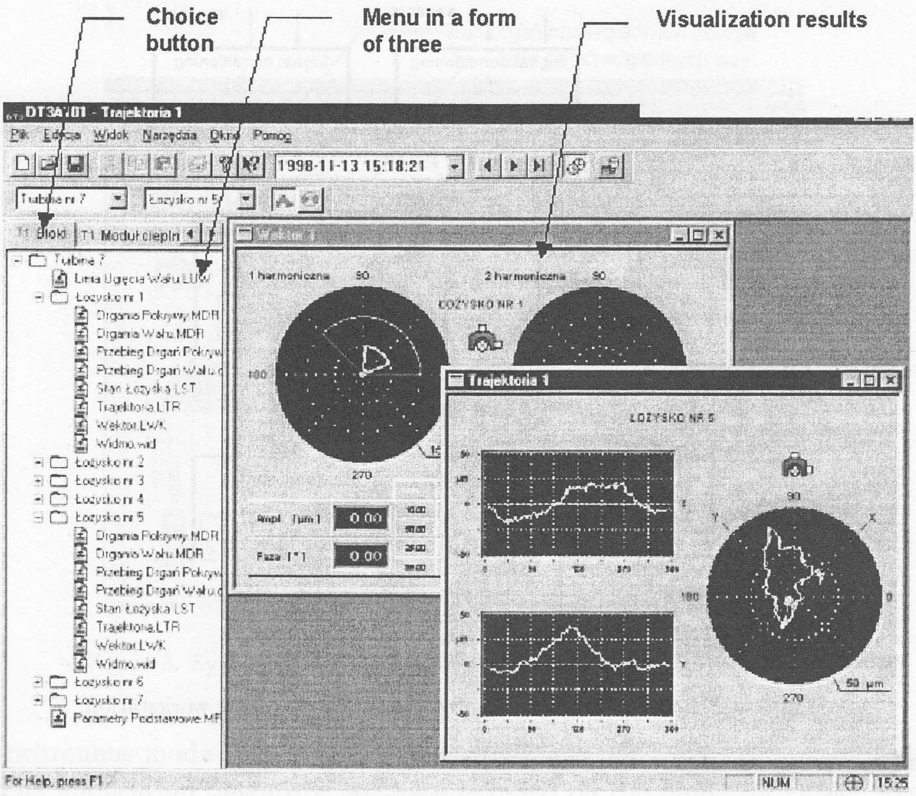


Figure 3. UI windows in DT200.

# 3 System modules, algorithms and software implementation

The main module of the system is processor workstation which realizes tasks related to signal acquisition and processing and sending the results to database using TCP/IP protocol. The data can be transferred to any computer which can work in Ethernet network with TCP/IP standard protocol. The processor workstation includes the following hardware components:

- Signal conditioning boards.
- Control and calibration board.
- AC signal conditioning board for vibration transducer.
- Keyphasor.
- Industrial VME computer with Ethernet.

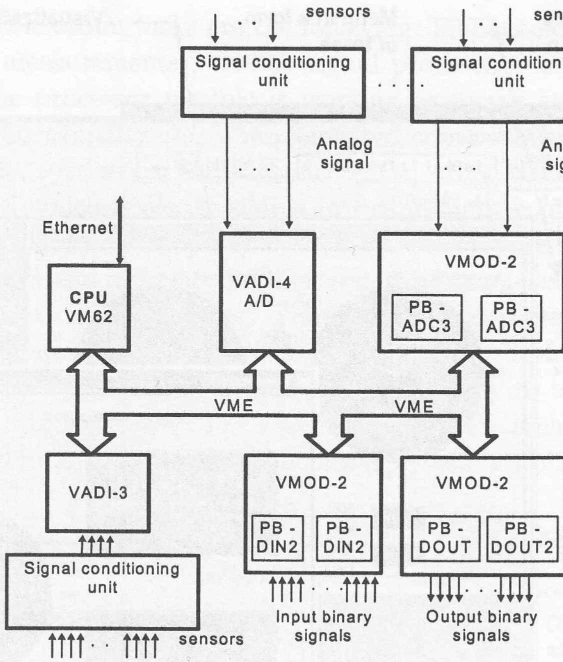


Figure 4. Scheme of hardware configuration for processor workstation.

- Power supply and stabilization unit (UPS).

The scheme of hardware is shown in Fig. 4.

Industrial computer is running under real time operating system VxWorks which provide task realization in a strictly safe time regime [3]. For example the system can acquire 144 binary signals during 2 ms, 32 AC signals during 1 s independently on turbine rotation speed or synchronously with shaft rotation. Response time of the system due to turbine unit shut down is 0.4 s. The most important tasks of the application software are:

- Setting of system configuration and management of measurement process.
- Signal acquisition.
- FTP server.
- Identification of the rotation speed and operation state of installation.
- Control of power supply.
- Calibration of inputs.

Keyphasor design is based on digital signal processor and is dedicated to control synchronous mode of signal acquisition [4,5]. Maximum rate of signal sampling

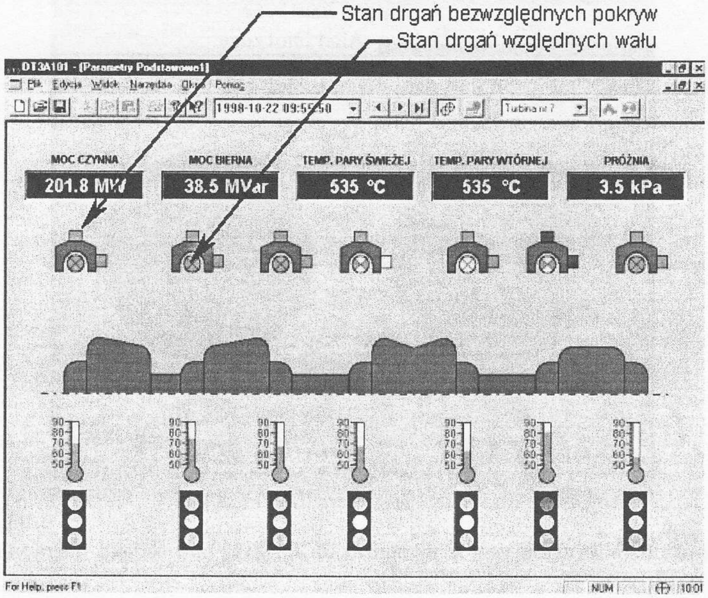


Figure 5. Synoptic table with general vibration state of turbine unit.

in synchronous mode is 128 samples per rotation.

The application diagnostic software is based on the limits for chosen symptom detects failures and realizes special measurement procedures to localize and assess damages. System configuration can be changed dynamically if system detects operation state which requires special measurements to detect damage. Standard FTP server which provides transfer of data from processor station to database is equipped with extra functionality, function *getx* that allows transferring data continuously, not only if standard function *get* is used.

Several [6] signal processing procedures are available in the system for asynchronic and synchronic data. Range of frequency analysis for asynchronic data is from 0 Hz to 20kHz, but for synchronic analysis range of frequency is limited to the following components; 1/3fo, 1/2fo, 2/3fo, 1fo,...,8fo. Resolution of synchronic analysis is 20 rpm. RMS and peak value of signals are basic estimates but some more advanced procedures including central moment up to fourth order, histograms are implemented in signal processing module in processor workstation.

Designed database works under Microsoft SQL Server which allows to cooperate with any external software not only DT200. In the database all data from processor workstation and control system (process data) are stored in files which are signed by time factor which is synchronized for all data sources.

Vibrodiagnostic module has implemented wide range of visualization services for whole measurements points. The symptom of measured signal is displayed on

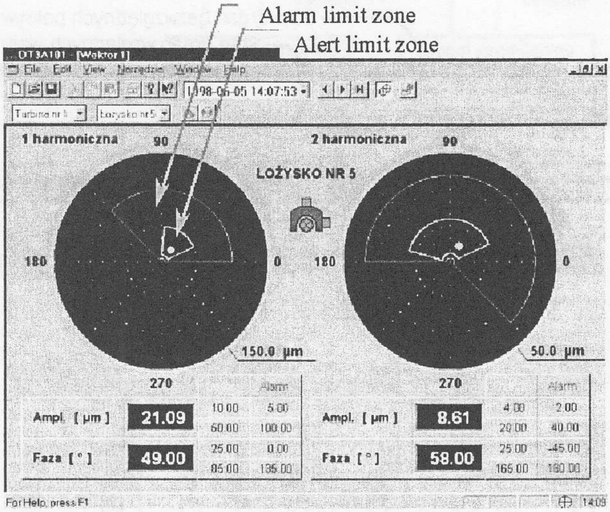


Figure 6. Vibration vector presentation for first and second harmonics.

synoptic table for turbine unit and detected state is indicated by the color. Typical screen shot for vibrodiagnostic module is shown in Fig. 5.

The shaft line can be displayed in two perpendicular directions, according to the location of sensors. At the same screen position of shaft center and interception of displacement limits are shown. Information related to whole shaft or to chosen set of bearings can be presented on the screen. In the system it is possible to assess unbalancing level and other shaft malfunction using the vibration vector for first, second, third and fourth harmonics (Fig. 6). The graphical presentation is completed with numerical one. All estimated signals characteristics and spectra with amplitude and phases are available. Damage assessment in designed system is possible by continuous trends observations of chosen vibration characteristics during operation time. Trends can be used for prediction of the symptom level. The normalized trends analysis is implemented. For normalized trends the influence of working conditions are filtered. Methods of linear regression, moving average, exponential smoothing are used for trend approximation. The module of process parameter measurements cooperate directly with the control system from which the process data are transferred into digital form. In the module economic, efficiency and technical parameters of process are investigated and displayed (Fig. 7).

Thermal stress monitoring is one of essential problem for thick-wall elements in turbine units, because large gradients of temperatures during the process start up, run down and changing of turbine load are the reasons for high level stress.

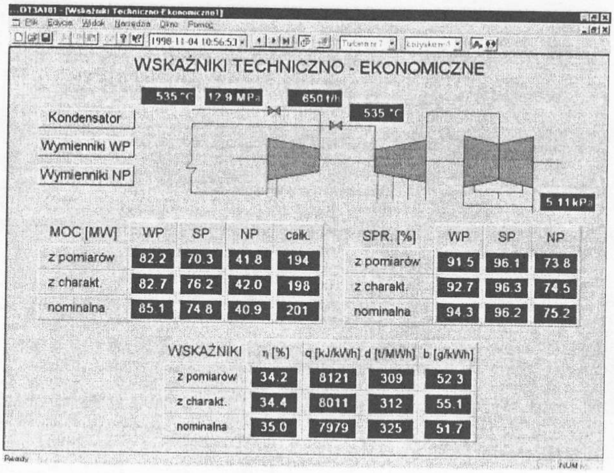


Figure 7. Display of process parameters analysis module.

The knowledge of stress history for particular elements of turbine is very helpful for durability assessment and maintenance planning. In the system thermal stress monitoring module is focused on critical elements that are chosen based on FEM model analysis. Stress is obtained based on temperature gradient estimation using metal temperature and process parameters measurements. Calculated stresses are compared with the limiting values. Limits are user defined. The fatigue counter is implemented in the system. Example of thermal stress monitoring window is shown in Fig. 8.

To detect machinery malfunction the limits for given symptoms should be defined. In the project many different symptoms have been used for this purpose. Based on knowledge of installation design and previous measurements that have been done on this machinery and similar, the limits are defined. The limits values differ from alarm values which are also implemented. The limits values are the symptoms amplitudes, if they are intercepting there is no danger situation for the structure but technical state should be very carefully tested or the operation parameters should be settled on the level which is safe for the installation.

The following damages can be detected using this approach: unbalancing, shaft misalignment, non-stability of oil film, rotor bending, bearing malfunction.

# 4 Simulation models

In the frame of the project the models describing dynamic behaviors of the shaft line-bearings-foundation have been developed. The models allow creation of

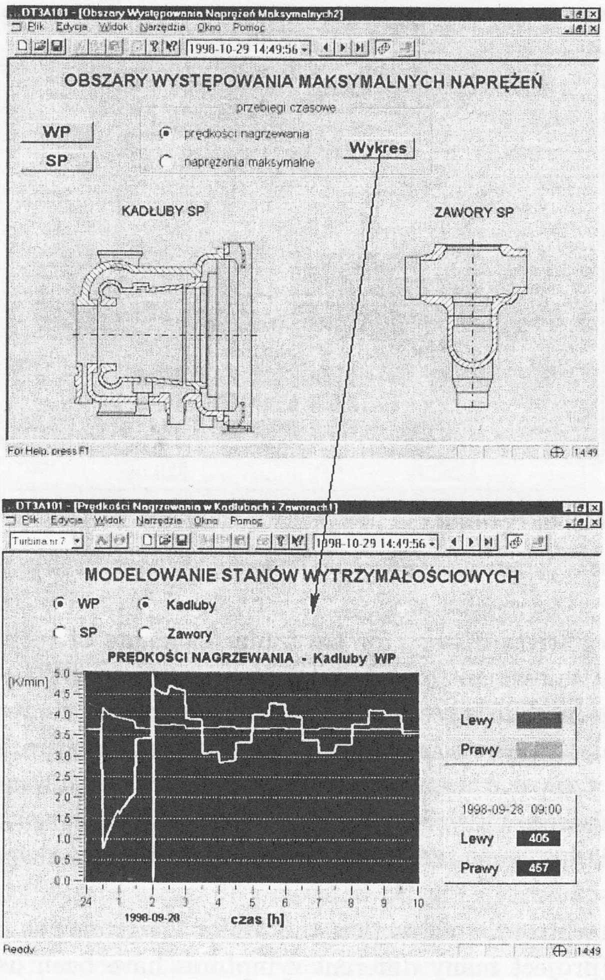


Figure 8. Thermal stress monitoring basic screen.

diagnostic cards that contain diagnostic relations about damage-symptom. Obtained in this way catalogue of diagnostic relations are included to database of expert system.

The code enables analysis of formulated models of the rotor-bearings-support system in the nonlinear range, i.e. calculates non-elliptic trajectories of selected node displacements for arbitrarily varying in time (but periodical) forces and external moments as well as a given system configuration (discs, dampers, journal and axial bearings, sealings, foundation, rotor imperfections of the crack and misalignment type) and enables construction of the vibration spectrum – Fig. 9.

The results of model simulation have been verified by experimental investiga-

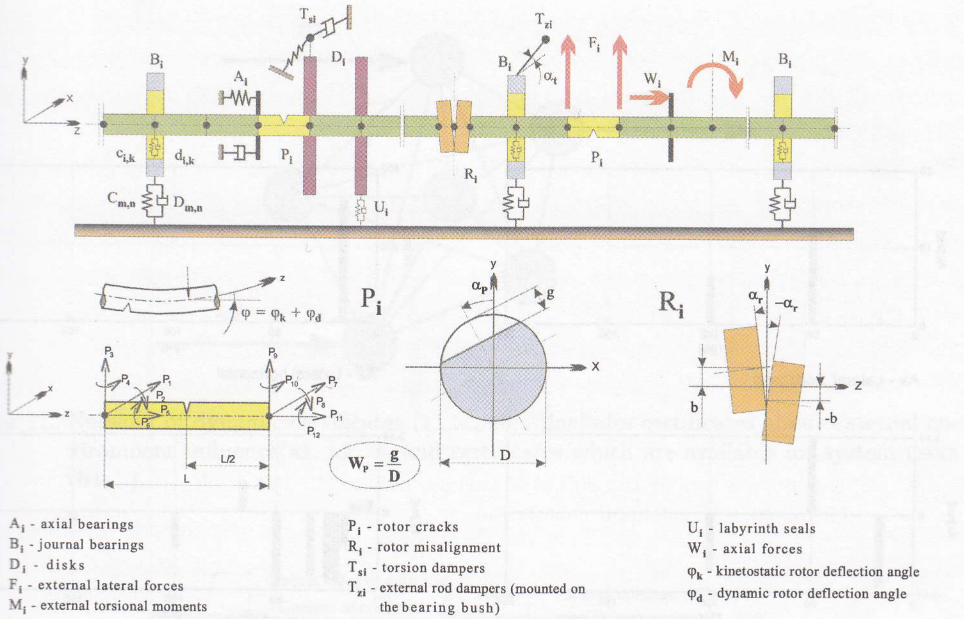


Figure 9. Calculational capabilities of a code for nonlinear rotor dynamics with imperfections.

tion of 200 MW turbine unit. An example of diagnostic relations obtained from simulation for shaft without crack and with crack is shown in Fig. 10.

# 5 Expert system

Implemented in DT200 expert system is a dynamic expert system which is dedicated for non-monotonic inference in variable environment [12, 13]. Mon-monotonic expert system means here that based on currently acquired data the system can change conclusions for opposite. Characteristic feature of dynamic expert system is the knowledge base that allows independent consideration of general diagnostic knowledge for high power turbine units and more detailed knowledge for particular installation element.

In implemented system net of certifications is a base for the design of database, knowledge base and reasoning system. The active certificates that represent opinion about installation and link concept of certificates, agents and frames are employed in the system. Active certificates can be treated as joint and cooperating nodes, which are continuously modified to achieve the balanced state by the entire network. Each node of such net can be modified by external tasks such as new measurements or by system users based on their experiences. Scheme of network

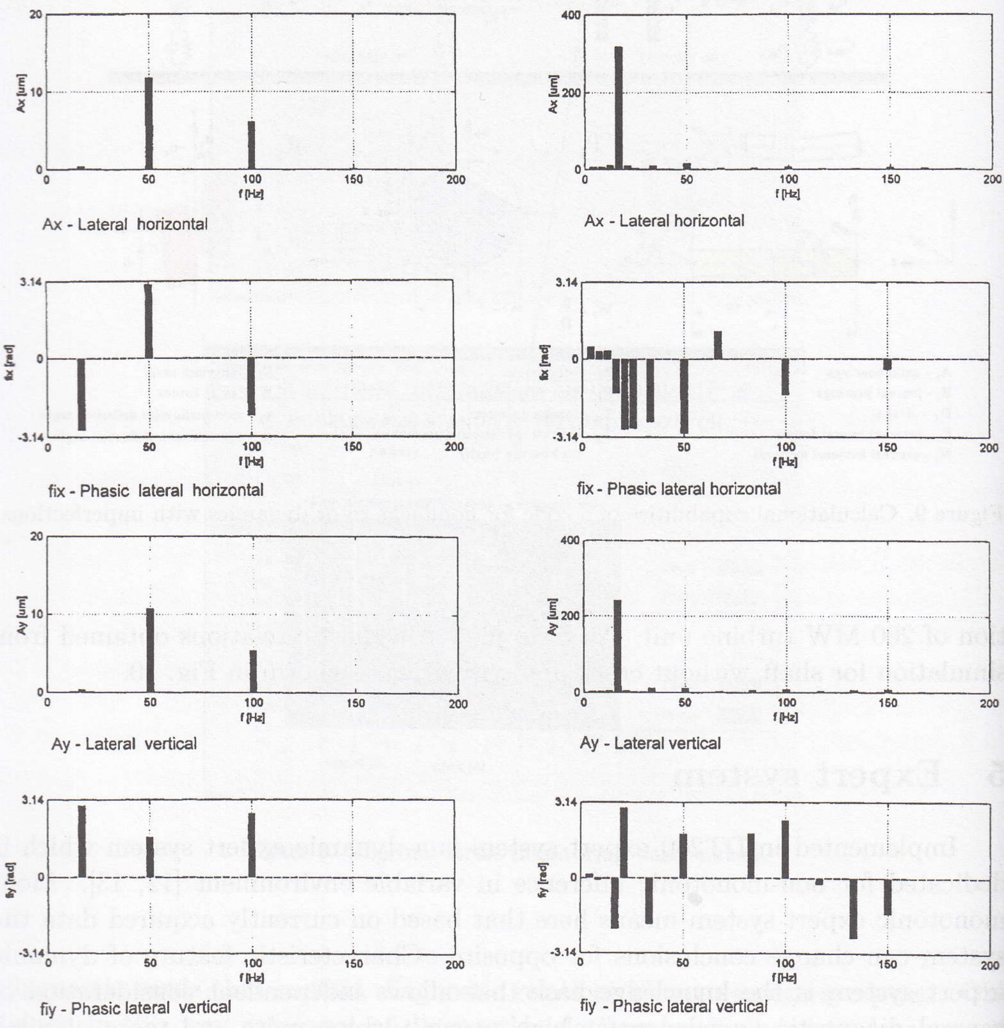


Figure 10. Components of amplitude spectra $A_x, A_y$ and phase spectra $fx$ and $fy$ calculated for the middle of the generator for the case without crack (left side picture) and with crack.

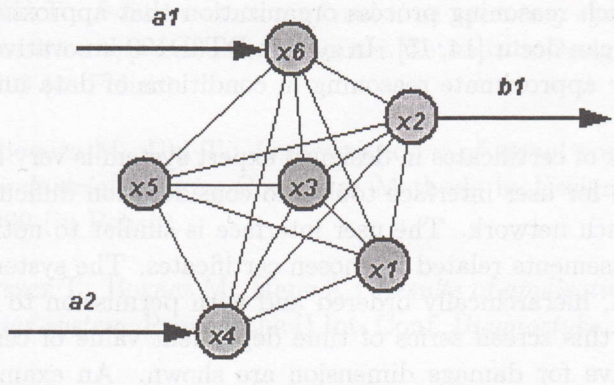


Figure 11. Network of dynamic certificates (x1,..., x6,...)includes certificates about external environment influence(a1, a2,...) and certificates which are available for system users (b1,...).

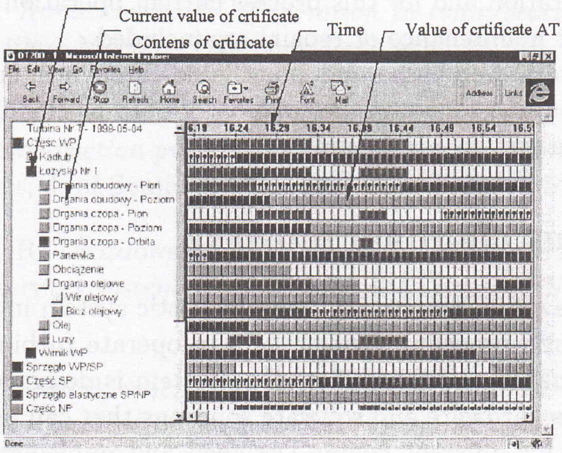


Figure 12. Main window of expert system with notice-board with color signed value of certificates which are informs of health of a system under investigation.

of certificates is shown in Fig. 11.

All certificates can change their value in time. Certificates, which occur as nodes of network, collect history of changes. This permits to repeat chosen previous situation by the system that can be applied for system verification or in order to generate descriptions proofing conclusions proposed by the system for current situation.

During research on diagnostic knowledge data base the authors found it impossible to represent precisely the diagnostic knowledge in many practical cases.

This requires such reasoning process organization that approximate and uncertain certificates can occur [14, 15]. In system DT3D100 innovative new algorithm which allows for approximate reasoning in conditions of data uncertainty is implemented.

The network of certificates in designed expert system is very large and implemented solution for user interface took into consideration difficulties in communication with such network. The user interface is similar to notice-board which contains advertisements related to chosen certificates. The system user has view of such a board, hierarchically ordered and with permission to change some of its details. On this screen series of time dependent value of certificates, which are representative for damage dimension are shown. An example of screen is shown in Fig. 12. Knowledge data base is designed as skeleton and empty. To fill the database many different numerical and experimental investigations have been done [16-18]. The knowledge data base fills continuously during machinery operations. Such design gives a big advantage because diagnostic knowledge is updated during operation and for this process current operation conditions (e.g. new conditions after maintenance or repair) are included.

The notice-board is web based and is available through internet using internet Explorer or Netscape software. Permission of data availability is controlled in the system by the system administrator.

# 6 Conclusions and final remarks

Presented in the paper monitoring and diagnostic system involves very wide spectrum of diagnostic procedures which help to operate turbine units and optimize their maintenance and durability. The system is designed with open architecture as regards hardware and software solutions that can be relatively easy extend and employ for different goals. Designed and implemented system has been tested on 200 MW turbine units and has been operating successfully for more then 5 years now.

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