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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**

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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:

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- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

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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## 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$^{\text{th}}$ 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, 179-190

JERZY GŁUCH*

# On implementation of selected methods of artificial intelligence in expert systems for thermal and flow diagnostics

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**Abstract**

Discussed has been a problem of aiding the operators of steam turbine cycles with the expert systems on the topic of exploitation decisions. Attention has been focused on realization of a one of the problems based on determination of the extent of exploitation degradation of geometric parameters of steam turbine blading. Discussion has been conducted on the sample of one of the components of the methods of artificial intelligence: a selected type of artificial neural network (ANN). Such ANN, which detects the extent of geometric degradation indicates a high quality and accuracy based on a good identification of the extent of degradation both in the case of complete and incomplete measurement data. In such way fulfilled are the requirements faced by the aiding methods regarding the automatic expert systems.

**Keywords:** Thermal and flow diagnostics; Expert systems; Neural networks

## 1 Modern thermal and flow diagnostics

Thermal and flow diagnostics is the element of automatic (computer-aided) expert system, which ensures a continuous operation of objects in thermal power engineering at relatively constant as well as high efficiency. The object of its interest is the economy of thermal processes [5, 15]. Its objective is a control of the adequacy of technical and economic indicators, such as specific heat consumption, with respect to the reference state [2, 5-7], as well as the response to detected impairment of those indicators. The reference state corresponds to the

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object operation at proper (not operationally degraded) geometric parameters of component devices. The indicators of correct (efficient) object operation are the symptoms defined as deviations between the values resulting from measurements for the actual state and corresponding values of the reference state. Definition of the symptom regards thermal and flow parameters such as: mass flow rate, pressure, temperature, as well as technical and economic parameters such as specific heat consumption. A lower value of the symptom from the measurement error confirms the correctness of operation. The set of symptoms forms a signature [4, 12, 15]. In the case of meeting impairment of the signature elements by the monitoring procedures there is a necessity to diagnose the object with the following aim:

- indicate malfunctioning object components [8],
- determine the geometric degradation type and their size [8].

As a result of such diagnosis there can be obtained circumstances to select, economically justified, exploitation decisions about further operation, the overhaul or modernization.
The concept of degradation is the exploitation wear of equipment leading to the change of its geometrical parameters. Such changes result in impairment of the course of thermal processes. Increase of the clearance in sealings or profile deformation in blade systems serve as examples of such degradation.
Analytical methods, considered as elements of the expert systems, based on implementation of full or simplified mathematical models of power engineering objects enable appropriate detection of their malfunctioning components [8]. Disadvantage of these methods is the necessity of employment of time consuming numerical models and a complicated interaction with the user. From amongst other methods, being the object of interest by the expert systems, which eliminate particularly the latter drawback, the artificial neural network (ANN) can be indicated.

As a result of the research conducted so far, [7], it has been concluded that ANN implementing the sigmoidal transfer functions are adequate for determination of the size of geometric degradation of power engineering objects on the basis of acquired signatures. They perform well in the case of single degradations, however in the case of multiple degradations they poorly detect the degraded geometric parameters [11].
On the other hand ANN, with the hard-lim transfer functions and adequate architecture of indication functions of malfunctioning components of thermal cycles and detection of the types of geometric degradations, can serve sufficiently in the case of multiple i.e. single-, double, triple, quadruple and primarily quintuple degradations [11]. Such networks possess also some ability for extrapolation

These can be used with reasonable results for the objectives described here.

The aim of the paper is to present the development of such idea based on implementation of operation of the ANN with the hard-lim transfer functions for aiding the selected type of ANN with sigmoidal transfer functions. Such combination of two types of ANN leads to the development of a user-friendly method of precise determination of the extent of geometric degradation of the blade system in power engineering turbine. According to [8] such a set of ANN can be regarded as an element of precise method of artificial intelligence aiding the computer expert system for the thermal and flow diagnostics. Trained ANN depicts the diagnostic relation and the process of data acquisition whereas training symbolises the development of diagnostic relation. Diagnostic relation is the dependence between the symptoms and the causes for malfunctioning operation. The object of presented research is the steam turbine cycle of 200 MW, where simulated have been numerically exploitation geometry degradations. Possibility of implementation of ANN has been tested on the basis of such simulation. Some part of the results of simulation calculations served for training of selected ANN whereas the remaining part were used for testing of trained ANN. Obtained results bring forward the time for practical implementation of methods of artificial intelligence in thermal and flow diagnostics.

## 2 Calculation model

Training of ANN requires supply of training data. Such data may come directly from measurements on existing objects. However the fields for measurements of the objects operationally degraded in the light of possible degradations are severely limited and hence that restricts the accuracy and the area of application of ANN developed on such basis. Of some help in extension of that range can be numerical simulations of degradation under condition of utilization in simulations of an adequate (physically correct) numerical model of arbitrarily complex model. The author is a member of the research team, which possesses such a tool – the code DIAGAR [1, 5], which performs balance calculations of cycles basing on 1-D models, where he developed the methodology of verification of calculations [13]. Mutual relations between the results of simulated calculations of a tuned model and the results on the real object are presented in Fig. 1. From the mathematical point of view operation of such model is based on determination of dependent variables in the calculation method, in the considered case: mass flow rate, pressures and cycle temperatures, on the basis of independent variables, geometric data and the cycle structure. The following set of parameters serves as independent variables:

- required by the contractor (the cycle power),

- independently preset by operators or resulting from the ambient conditions (pressure and temperature of fresh steam, secondary steam temperature, condensation and deareting pressure and finally mass flow rate of water injections to boilers).

The results of investigations presented in the paper have been obtained using the tool described above.

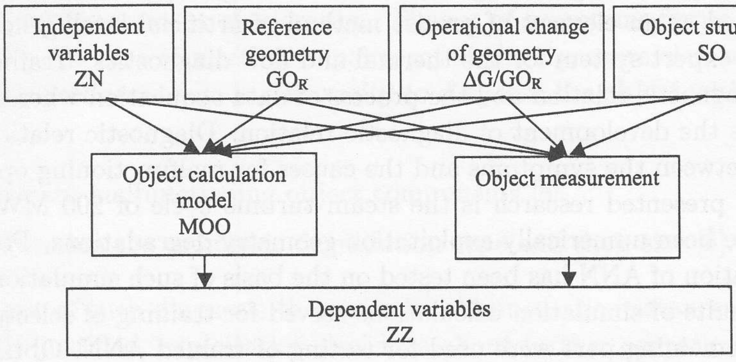


Figure 1. Relations between the results of calculations of a tuned model of the object and the results of real measurements of the power unit.

# 3 Description of the diagnosed object

Analysed power engineering object, presented for instance in [9] and [10], consists of several devices connected in a different way. There are localised several measurement points of thermal and flow properties, but despite that not all the component devices are fully measured.
In the present work the measurement locations regarding the cylinders of both the HP and IP of main turbine have been considered in diagnostic analysis. Measurements of **power, live steam flux, pressures in control stage chamber and regeneration bleedings and temperatures in regeneration bleedings** were regarded as feasible for taking thermal and flow properties measurements. Their values depend on, in the first instance, the flows resulting from the cycle load and its structure, as well as structure of turbine, and subsequently on operational degradation of devices.

# 4 Simulation calculations of geometric degradation

The results of measurements, difficult to be obtained in practice, connected unanimously with operational geometry degradation, have been replaced, for the

Table 1. Identification numbers for geometrical parameters subject to operating degradation within HP and IP casings.

| Identifier | Name of geometrical parameter, subject to degradation |
|---|---|
| 1 | HP control valve nozzle box sealing clearance |
| 2 | HP external gland clearance |
| 3 | HP stage group No. 1 sealing clearance |
| 4 | HP stage group No. 1 blade system roughness |
| 5 | HP stage group No. 1 profile trailing edges |
| 6 | HP stage group No. 2 sealing clearance |
| 7 | HP stage group No. 2 blade system roughness |
| 8 | HP stage group No. 2 profile trailing edges |
| 9 | IP control valve nozzle box sealing clearance |
| 10 | IP external gland clearance |
| 11 | IP stage group No. 3 sealing clearance |
| 12 | IP stage group No. 3 blade system roughness |
| 13 | IP stage group No. 3 profile trailing edges |
| 14 | IP stage group No. 4 sealing clearance |
| 15 | IP stage group No. 4 blade system roughness |
| 16 | IP stage group No. 4 profile trailing edges |
| 17 | IP stage group No. 5 sealing clearance |
| 18 | IP stage group No. 5 blade system roughness |
| 19 | IP stage group No. 5 profile trailing edges |
| 20 | IP stage group No. 6 sealing clearance |
| 21 | IP stage group No. 6 blade system roughness |
| 22 | IP stage group No. 6 profile trailing edges |

sake of presentation of results, with the results of simulation calculations for assumed values of such degradations. In simulation calculations considered have been intermediate degrees of degradation between the null values and maximum allowable (in the range 0÷100% of maximum degradation) as well as different combinations of single, double, triple, quadruple and quintuple degradations. The turbine cycle for simulation calculations of degradations has been numerically modelled by means of a 1-D calculation method using the code DIAGR [1, 3], tuned to reliable measurement results of one from the existing units incorporating the 200 MW turbine. On the basis of design of that particular turbine and possible in exploitation maximum degradations of geometry systematically have been varied geometric parameters from the reference values down to fully degraded ones. A list of considered geometric parameters, subject to degradation process, has been presented in Tab. 1.

# 5 Development of diagnostic relations – determination of the size of geometric degradation

The principles of utilisation of simulation calculations for acquisition of data for diagnostic relations have been presented in Fig. 2. A set of data has been supplemented with respect to the calculation method flow-chart from Fig. 1 for the degradation code, KTD, in order to obtain a better perceptibility of ANN. KTD has been defined for example in [11] as a zero-one set of numbers, symbolizing the reasons for geometry degradation, where the order of appearance is consistent with notation in Tab. 1. Assumed convention in the KTD code reads: 1 – appearance of particular degradation cause; 0 – non-degraded geometric parameter.

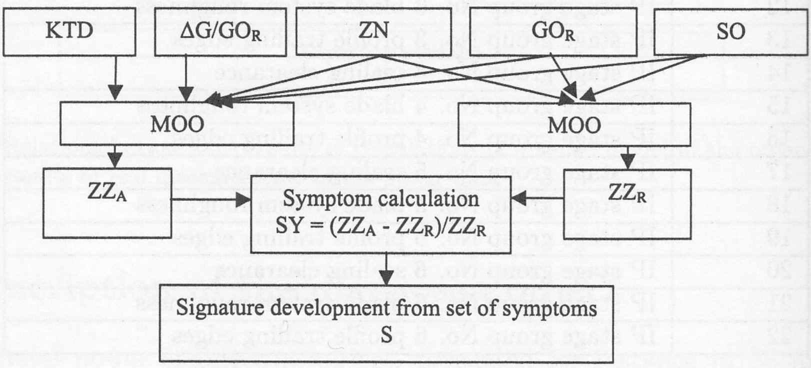


Figure 2. Principles of implementation of simulation calculations in acquisition of diagnostic relations (description relates to Fig. 1).

At the simulation procedure the extent of degradation together with the resulting KTD code are being assumed. On the other hand, in practical implementation such KTDs are the results of performed, in the first instance, accurate ANN calculations with hard-lim transfer functions, in order to localise the reasons of geometric degradation [11]. In such a way realised is, signalled earlier, principle of implementation of two types of ANN in order to obtain a high accuracy of diagnosis. Combination of the causes of degradation used in ANN training has been symbolically presented in Tab. 2.

In Fig. 3 illustrated is a diagnostic relation as an inverse model of a complex object. Apparently, obtaining of analytical form of inverse model is very difficult,

Table 2. Symbolic interaction between the input data and selected output data for ANN training.

| Degradation | Signature number | KTD | | | | | | Extent of geometric changes | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | P1 | P2 | P3 | P4 | ... | P22 | ΔG1 | ΔG2 | ΔG3 | ΔG4 | ... | ΔG22 |
| single | S0001 | 1 | 0 | 0 | 0 | ... | 0 | 0.25 | 0 | 0 | 0 | ... | 0 |
| | S0002 | 0 | 1 | 0 | 0 | ... | 0 | 0 | 0.25 | 0 | 0 | ... | 0 |
| | S0003 | 0 | 0 | 1 | 0 | ... | 0 | 0 | 0 | 0.25 | 0 | ... | 0 |
| | S0004 | 0 | 0 | 0 | 1 | ... | 0 | 0 | 0 | 0 | 0.25 | ... | 0 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | S0022 | 0 | 0 | 0 | 0 | ... | 1 | 0 | 0 | 0 | 0 | ... | 25 |
| | S0023 | 1 | 0 | 0 | 0 | ... | 0 | 0.50 | 0 | 0 | 0 | ... | 0 |
| | S0024 | 0 | 1 | 0 | 0 | ... | 0 | 0 | 0.50 | 0 | 0 | ... | 0 |
| | S0025 | 0 | 0 | 1 | 0 | ... | 0 | 0 | 0 | 0.50 | 0 | ... | 0 |
| | S0026 | 0 | 0 | 0 | 1 | ... | 0 | 0 | 0 | 0 | 0.50 | ... | 0 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | S0044 | 0 | 0 | 0 | 0 | ... | 1 | 0 | 0 | 0 | 0 | ... | 0.50 |
| | S0045 | 1 | 0 | 0 | 0 | ... | 0 | 0.75 | 0 | 0 | 0 | ... | 0 |
| | S0046 | 0 | 1 | 0 | 0 | ... | 0 | 0 | 0.75 | 0 | 0 | ... | 0 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | S0066 | 0 | 0 | 0 | 0 | ... | 1 | 0 | 0 | 0 | 0 | ... | 0.75 |
| | S0067 | 1 | 0 | 0 | 0 | ... | 0 | 1.00 | 0 | 0 | 0 | ... | 0 |
| | S0068 | 0 | 1 | 0 | 0 | ... | 0 | 0 | 1.00 | 0 | 0 | ... | 0 |
| | S0069 | 0 | 0 | 1 | 0 | ... | 0 | 0 | 0 | 1.00 | 0 | ... | 0 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | S0088 | 0 | 0 | 0 | 0 | ... | 1 | 0 | 0 | 0 | 0 | ... | 1.00 |
| double | S0089 | 1 | 1 | 0 | 0 | ... | 0 | 1.00 | 1.00 | 0 | 0 | ... | 0 |
| | S0090 | 1 | 0 | 1 | 0 | ... | 0 | 1.00 | 0 | 1.00 | 0 | ... | 0 |
| | S0091 | 1 | 0 | 0 | 1 | ... | 0 | 1.00 | 0 | 0 | 1.00 | ... | 0 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | S0111 | 0 | 1 | 1 | 0 | ... | 0 | 0 | 1.00 | 1.00 | 0 | ... | 0 |
| | S0112 | 0 | 1 | 0 | 1 | ... | 0 | 0 | 1.00 | 0 | 1.00 | ... | 0 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | S0133 | 0 | 0 | 1 | 1 | ... | 0 | 0 | 0 | 1.00 | 1.00 | ... | 0 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| triple | S0320 | 1 | 1 | 1 | 0 | ... | 0 | 1.00 | 1.00 | 1.00 | 0 | ... | 0 |
| | S0321 | 1 | 1 | 0 | 1 | ... | 0 | 1.00 | 1.00 | 0 | 1.00 | ... | 0 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | S0339 | 1 | 1 | 0 | 0 | ... | 1 | 1.00 | 1.00 | 0 | 0 | ... | 1.00 |
| | S0340 | 1 | 0 | 1 | 1 | ... | 0 | 1.00 | 0 | 1.00 | 1.00 | ... | 0 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | S0358 | 1 | 0 | 1 | 0 | ... | 1 | 1.00 | 0 | 1.00 | 0 | ... | 1.00 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| quadruple | | | | | | | | | | | | | |
| | S1860 | 1 | 1 | 1 | 1 | ... | 0 | 1.00 | 1.00 | 1.00 | 1.00 | ... | 0 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | S1878 | 1 | 1 | 1 | 0 | ... | 1 | 1.00 | 1.00 | 1.00 | 0 | ... | 1.00 |
| | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | S9174 | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... | 1.00 |

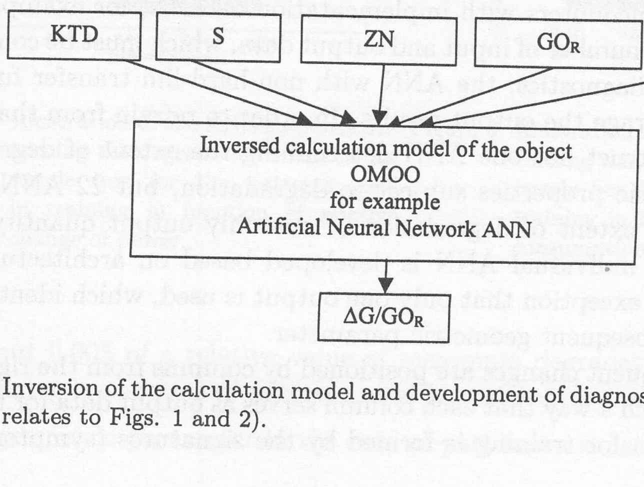


Figure 3. Inversion of the calculation model and development of diagnostic relations (description relates to Figs. 1 and 2).

and at present capabilities almost impossible, however implementation of ANN leads to its replacement by the adequate and trained ANN. In Fig. 4 symbolically presented is an artificial neural network with non-hard-lim transfer function, which can be regarded as an inverse calculation model of the object. The ANN trained in such a way serves as a diagnostic relation.

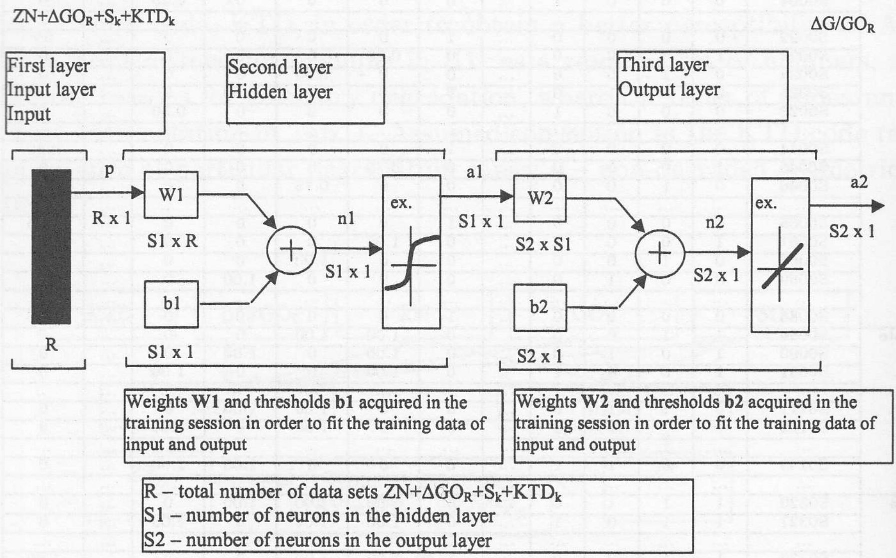


Figure 4. Architecture of ANN with non-hard-lim transfer functions according to [3, 14].

# 6 Accuracy of diagnostic relations based on ANN

Earlier author's encounters with implementation of ANN, for example [6-8], showed that at a large number of input and output data, which must be considered in thermal and flow diagnostics, the ANN with non-hard-lim transfer functions has a tendency to average the output results. In order to refrain from that it has been decided to construct not one ANN determining the extent of degradation of each of 22 geometric properties subject to degradation, but 22 ANN, where each one detects the extent of degradation of one only output quantity of 22. Architecture of each individual ANN is developed based on architecture from Fig. 4, with the only exception that only one output is used, which identifies the relative change of subsequent geometric parameter.
In Tab. 2 such subsequent changes are positioned by columns from the right hand side of the table in such a way that each column serves as output data for training. The set of input data for training is formed by the signatures (symptoms) and

all corresponding KTD codes positioned on the left hand side of Tab. 2. Effectiveness of a system consisting of two kinds of neural networks has been exposed to verification based on investigations of accuracy of response of trained subsequent 22 ANN. Investigated has been the response to the patterns used in training and not used in training. Presented here patterns, which were not used in training, stem from simulation calculations of degradation. The patterns not used in training regarded:

- ranges of 33% and 66% of maximum exploitation change of geometric parameters for assumption of single degradation,
- combination of ranges of 25%, 50% and 75% of maximum change of exploitation geometric parameters for assumed double and triple degradation.

Examples of the network response error to the assumed pattern have been presented graphically in the simplified two-dimensional spaces in Fig. 5 and 6 for the patterns used in training and in Fig. 5 and 6 for the patterns not used in training. The error of response symbolises graphically the distance between the pattern and the network response.

An average value of that distance (error) is:

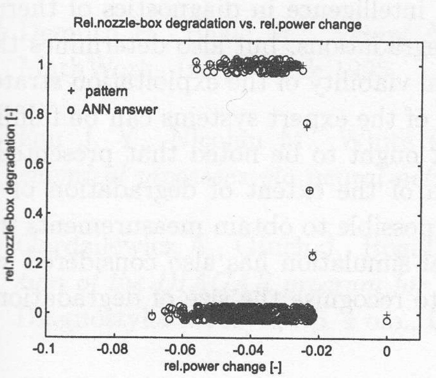


Figure 5. Illustration of the ANN response discerning the degradation range in the nozzle box for the patterns used in training in function of relative change of power.

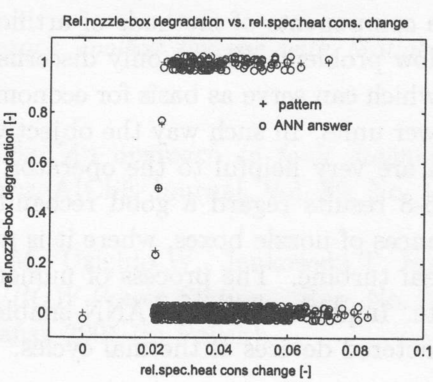


Figure 6. Illustration of the ANN response discerning the degradation range in the nozzle box for the patterns used in training in function of specific heat consumption.

- about 0.005 of a relative value of maximum degradation of geometric parameter in the case of patterns used in training,
- of geometric parameter in the case of patterns not used in training.

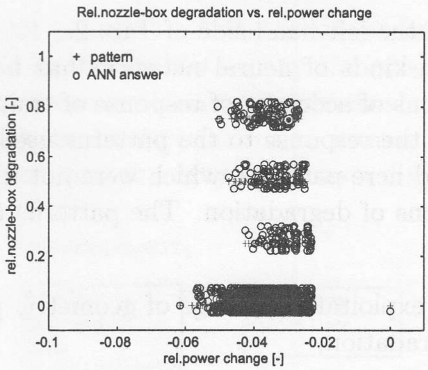


Figure 7. Illustration of the ANN response discerning the degradation range in the nozzle box for the patterns not-used in training in function of relative power change.

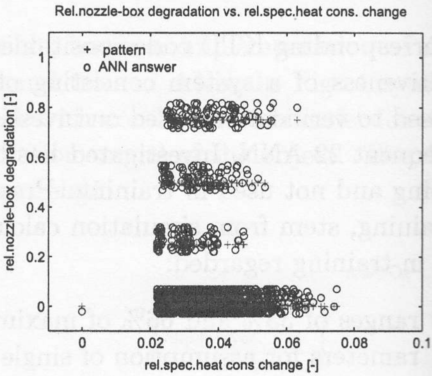


Figure 8. Illustration of the ANN response discerning the degradation range in the nozzle box for the patterns not-used in training in function of relative specific heat consumption change.

Such recognition of the extent of geometric degradation is characterised by a small value of error. This lays out good perspectives for implementation of ANN as one of the components of methods of artificial intelligence in diagnostics of thermal and flow problems. It not only discerns degradations, but also determines their size, which can serve as basis for economical viability of the exploitation strategy of power units. In such way the objectives of the expert systems can be fulfilled, which are very helpful to the operator. It ought to be noted that presented in Fig. 5-8 results regard a good recognition of the extent of degradation of the clearances of nozzle boxes, where it is not possible to obtain measurements from the real turbine. The process of numerical simulation has also considered such a state. Implementation of ANN enables to recognise the size of degradation of non-metered devices of thermal cycles.

# 7 Conclusions

Presented has been a method of implementation of ANN which can exist as an element of artificial intelligence in the expert system for aiding the thermal and flow diagnostics of power engineering units.

Postulated has been the mode of co-operation between two types of ANN, one with the hard-lim transfer function and the other one, with sigmoidal transfer functions.

Operation of such networks has been verified based on simulation calculations of exploitation degradation using the adequate calculation model tuned to operation

of one of the domestic power engineering units incorporating turbine of 200 MW. A good quality of recognition of the extent of degradation of the geometry of the flow system of steam turbine has been concluded, Fig. 5–8.
Postulated ANN are relatively easy to be coded in the computer system with a user-friendly interface.
A good recognition and a user-friendliness lays ground for implementation of such sets of ANN in the expert system, as in the result of their operation there can be conducted the process of automatic concluding.

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