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Effectiveness investigation of the RBF-neural network applied to modelling of the ship propulsion systems with controllable pitch propeller (CPP)

SUMMARY

Using the controllable pitch propellers (CPP) on ships introduces, apart from the rotational propeller speed N an additional degree of freedom: the pitch ratio P/D of the propeller, increasing the setting space of the propulsion system but also imposing the necessity of the optimum setting determination. To realize the aim, as accurate as possible characteristics of the propulsion system must be at disposal.

The characteristics can be determined with the use of both the conventional mathematics and artificial intelligence methods such as neural networks or fuzzy logic. The paper presents a method of neural modelling of the propulsion system and results of the experiments which makes evaluation of the network effectiveness posssible.

INTRODUCTION

A scheme of the ship propulsion system with CPP is depicted in Fig.1.

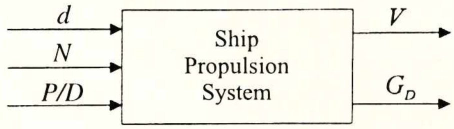


***Fig.1.** Ship propulsion system in terms of inputs, outputs, and disturbances*

N - *rotational propeller speed [rpm]*, P/D - *pitch ratio [mm/mm]*, V - *ship speed [knots]*, G_D - *fuel consumption [kg/day]*, d - *disturbances influencing the hull resistance [N]*

A demanded ship speed can be obtained in the CPP propulsion system at infinitely large number of *N* - and *P/D*-settings. But only one pair of the settings gives the minimum fuel consumption. To determine the optimum settings the 3-dimensional characteristics :

$$V = f_1(N, P/D) \quad \text{and} \quad G_D = f_2(N, P/D)$$

for various operating conditions must be at disposal. The roughest (fuzzy) classification of the conditions can be obtained by dividing them into the following classes :

- the conditions which **increase** the hull resistance (head wave, wind and current, big load and draught, unfavourable trim, low calorific fuel value, small water depth, etc.
- the conditions which **decrease** the hull resistance (stern wave, wind and current, small load and draught, favourable trim, big fuel calorific value, sufficiently big depth, etc.) and
- the **neutral** ones.

A more accurate division into 5 or more classes is also possible. The best solution would be to determine separate characteristics for each condition class and use them in the system control. Characteristics of the ship propulsion system are the clue to the fuel consumption minimization problem. Therefore investigations on their determining have been realized in Poland [1,2,3,4,6,11] and abroad [5,7,10,12] for many years. The characteristics $V=f_1(N,P/D)$ and $G_D=f_2(N,P/D)$ were usually determined from 3 separate characteristics of the propulsion system elements: engine, propeller and hull [1,3,7,11], at the designer disposal, Fig.2.

According to [3] and other sources, influence of the disturbances d_i is not big and therefore often neglected. The propulsion system is usually described in terms of the conventional mathematics [3,11], e.g. by using polynomials as follows (1) :

$$T = K_T \varsigma D^4 N^2$$

$$K_T = g_0 + g_1 J + g_2 J^2 + (P/D)\left(g_3 + g_4 J + g_5 J^2\right) + + (P/D)^2\left(g_6 + g_7 J + g_8 J^2\right) \quad (1)$$

where:
J - advance coefficient of the propeller
g_i - polynomial coefficients.

The approach of splitting the propulsion system shown in Fig.1 into the subsystems shown in Fig.2 is called the *white box approach* in terms of the control theory. The subsystems are easier to analyze,

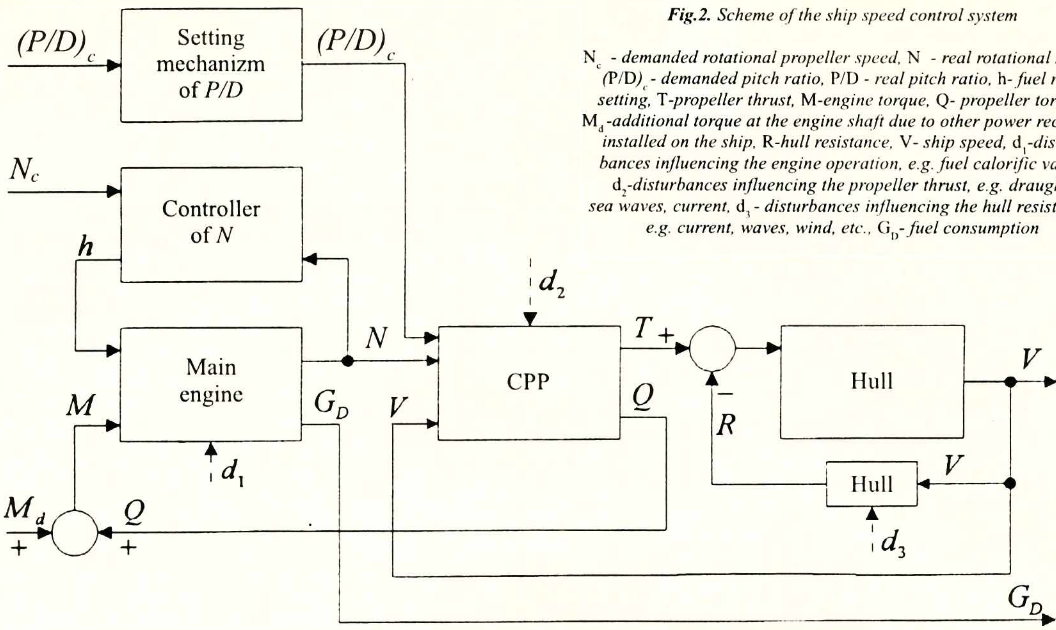


Fig.2. Scheme of the ship speed control system

N_c *- demanded rotational propeller speed,* N *- real rotational speed,* $(P/D)_c$ *- demanded pitch ratio,* P/D *- real pitch ratio,* h*- fuel rack setting,* T*-propeller thrust,* M*-engine torque,* Q*- propeller torque,* M_d *-additional torque at the engine shaft due to other power receivers installed on the ship,* R*-hull resistance,* V*- ship speed,* d_1*-disturbances influencing the engine operation, e.g. fuel calorific value,* d_2*-disturbances influencing the propeller thrust, e.g. draught, sea waves, current,* d_3 *- disturbances influencing the hull resistance, e.g. current, waves, wind, etc.,* G_D*- fuel consumption*

understand and describe than the entire system which contains them. To describe the subsystems in terms of the conventional mathematics a form (structure) of mathematical formulae e.g. (1) must be assumed a priori. Then all their coefficients are to be identified. Such approach causes the following errors :

- error due to a structure of the formulae and number of their elements
- error due to identification of the coefficients.

If signs and values of particular errors are unfavourable the global model error will be very large. Such situation is highly probable as the number of all coefficients in the formulae describing the propulsion system is large and identification accuracy of the coefficients, particularly hydrodynamic ones, is limited. An alternative to the white box approach is the *black box* one where the system is considered as an entity, Fig.1. In this case the input/output causalities $V = f_1[N_c,(P/D)_c]$ and $G_D = f_2[N_c,(P/D)_c]$ are directly modelled and the inner system signals, such as *Q, R, T, M,* must not be considered. The *black box* system modelling is difficult in use because the complex systems are almost always nonlinear, whereas their subsystems can be linear or weakly nonlinear. Modelling of the nonlinear systems can be realized by means of the conventional mathematics. However, as in the case of the subsystems, a certain structure must be assumed for the formulae, which is a source of errors. The neural modelling method presented below, called the *error residua method* [9], self-organizes its structure (i.e. structure of formulae) and tunes (i.e. identifies) its coefficients appropriately to measurement input/output data and to a required modelling accuracy (lower accuracy - less neurons, higher accuracy - more neurons). The investigation made by the authors shows that the proposed method applied to modelling the ship propulsion system can be very effective. The system inputs, *N* and *P/D*, are equal, on the average, to their demanded values, N_c and $(P/D)_c$,within relatively long periods of a few hours :

$$N \cong N_c \qquad P/D \cong (P/D)_c$$

Therefore the variables can be exchangeably assumed to serve as the model inputs, Fig.1. Measuring the ship speed *V* does not cause any difficulty as the satellite positioning systems are broadly used today and their accuracy is very high. Fuel consumption measurements can be periodically made (e.g. 2 times per hour) by using fuel measurement tanks. The tanks are usually installed on one or more ships of each series built in the shipyards. The training ship *Nawigator XXI* of the Maritime University of Szczecin is equipped with such tank. Also fuel flow sensors at the fuel inlet and return pipe can be installed. Direct onboard measurements of all variables are feasible and make it possible to account for :

- current state (after adjustments, repairs) of the engine and other propulsion system elements
- conditions occurring on a given trade line (mean weather conditions, magnitude and direction of currents).

The direct onboard measurements have significant advantages against the on-shore measurements carried out on the separate elements of the propulsion system (new-engine characteristics made by its producer, hull and propeller characteristics determined at a ship model basin).

NEURAL MODELLING WITH THE USE OF THE ERROR RESIDUA METHOD

In the first step the surface S of the $X \rightarrow Y$ (inputs→output) mapping is split into the base model M_0 and error model E_0, as follows (2) :

$$S = M_0 + E_0 \qquad (2)$$

The base model M_0 consists of only one multidimensional, expanded RBF (radial basis function) neuron expressed by (3) :

$$y_0 = b_0 \exp\left(-\sum_{j=1}^{k}\left|\frac{x_j - m_{j0}}{\delta_{j0}}\right|^{l_{j0}}\right) + a_0 \qquad (3)$$

where : k - number of inputs.

The base model (base neuron) is a generalization of the $X \rightarrow Y$ mapping and is not always sufficiently accurate. But its accuracy can be increased.

In the second step the measurement point A_1 is found whose absolute error value $|e_0|$ is maximal. In this point the second RBF neuron which models the error E_0, is placed to start the learning process. In the process the neuron E_{0M} fills in one error „mountain" or „valley". After this step the model consists of 2 neurons : M_0 and E_0. To model the error the expanded RBF neurons expressed by function (4) are used :

$$e_{0M} = b_{0M} \exp\left(-\sum_{j=1}^{k}\left|\frac{x_j - m_{j0M}}{\delta_{j0M}}\right|^{l_{j0M}}\right) \qquad (4)$$

The neuron E_{0M} seldom fits exactly to all measurement points. Therefore in the succeeding step the first error residuum E_1, according to (5) :

$$E_1 = S - (M_0 + E_{0M}) \qquad (5)$$

is calculated for each measurement sample and the point A_2 of the greatest absolute error value $|e_i|$ is found. In this point the third RBF neuron is placed for starting the learning process. After the learning the neuron E_{1M} fits to one error „mountain" or „valley". It is added to the previous neurons and a model consisting of 3 neurons is now obtained. If accuracy of the model is not sufficient, an error residuum is calculated according to (6) :

$$E_2 = S - (M_0 + E_{0M} + E_{1M}) \qquad (6)$$

and the network is expanded by the next neuron, similarly as in the previous step. The greater number of the neurons the greater accuracy of the model in result of successive modelling one error „mountain" after another. The modelling is continued until a satisfactory accuracy is obtained.

BLACK BOX MODELLING OF THE SHIP PROPULSION SYSTEM

The first author realized a modelling experiment according to the error residua method. 65 measurements being at his disposal are given in the normalized form (related to the interval {0,100}) in Tab.1. The values calculated on the basis of the data from [6] refer to a mean loading state of the ship *Skulptor Konenkov.*

Tab.1. *Normalized measurement data of the mean loading state of the ship Skulptor Konenkov*

Parameters	Measurement No.						
	1	2	3	...	63	64	65
N_n	0	3.918	13.594	...	72.009	85.099	100.0
P/D_n	100.0	75.0	48.6	...	48.6	24.9	0
G_{Dn}	1.905	0.322	0	...	72.637	83.375	100.0
V_n	0	0	0	...	100.0	100.0	100.0

The aim of modelling was to determine :

the speed model $V_n = f_1[N_n,(P/D)_n]$
fuel consumption model $G_{Dn} = f_2[N_n,(P/D)_n]$

and on their basis to determine a 4-dimensional optimal control trajectory $[V_n, G_{Dn.min}] = f[N_n,(P/D)_{n,opt}]$. In the first modelling step the base models (neurons) were found after the learning process. The base neuron of the speed is given by (7). The mean absolute error of the model is equal to 0.7978.

$$V = 364.1\exp\left(-\left|\frac{0.97N + 0.22P/D - 111.04}{135.35}\right|^{1.64} + -\left|\frac{-0.22N + 0.97P/D - 85.68}{402.90}\right|^{1.62}\right) - 231.94 \qquad (7)$$

The neuron is depicted in Fig.3, and Fig.4 illustrates a fragment of the base speed neuron comprising the space of measurement samples.

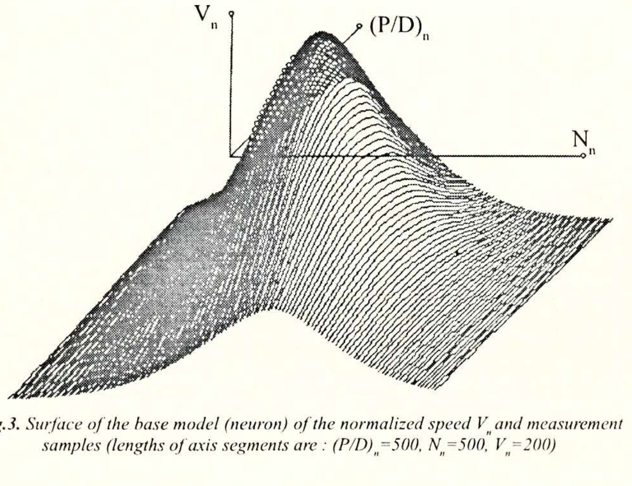


Fig.3. *Surface of the base model (neuron) of the normalized speed V_n and measurement samples (lengths of axis segments are : $(P/D)_n$=500, N_n=500, V_n=200)*

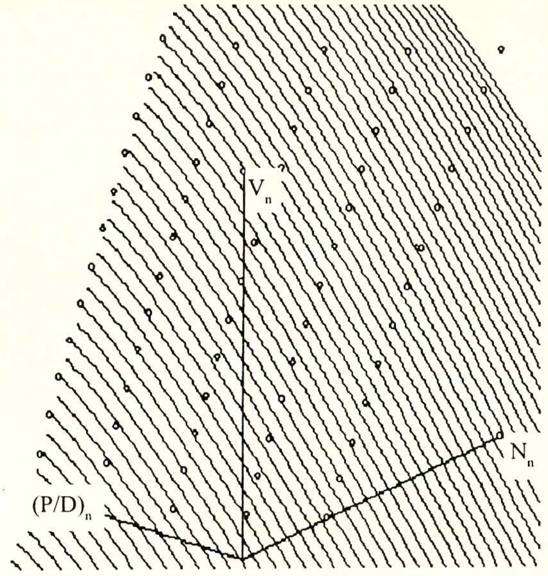


Fig.4. *A fragment of the V -speed base neuron comprising the space of normalized measurement samples {lengths of axis segments are : $(P/D)_n$=100, N_n=100, V_n=100}*

The base neuron of the normalized fuel consumption:

$$G_{Dn} = f_2[N_n,(P/D)_n]$$

and its augmented fragment is depicted on Fig.5 and 6, respectively.

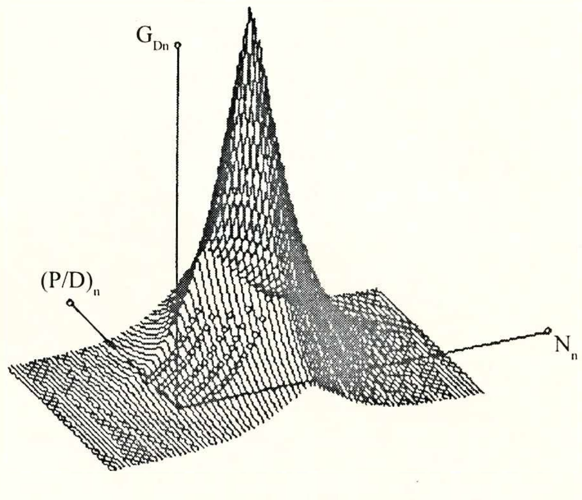


Fig.5. *Base neuron surface of the normalized fuel consumption G_{Dn} with indicated measurement points {lengths of axis segments are : $(P/D)_n$=400, N_n=400, V_n=400}*

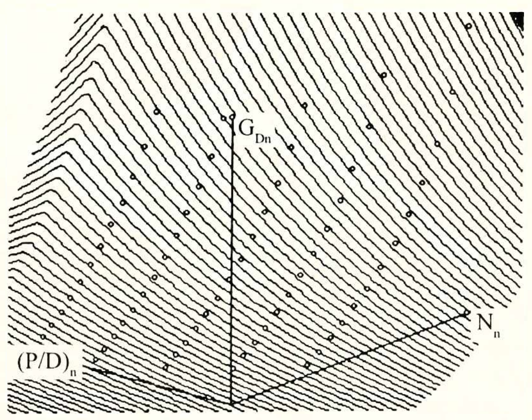
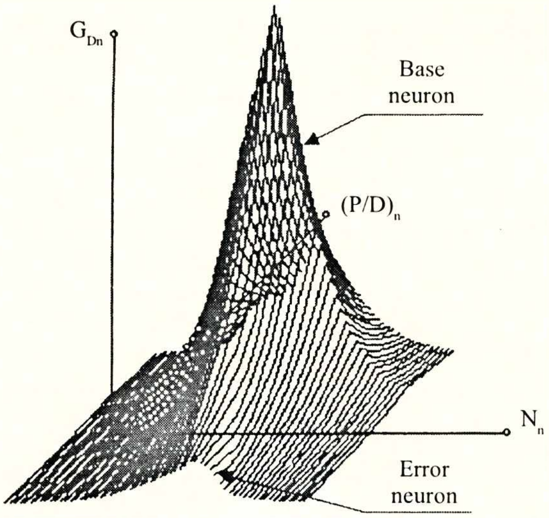


Fig.6. *A fragment of the base neuron of the normalized fuel consumption comprising the measurement samples space {lengths of axis segments are : $(P/D)_n$=100, N_n=100, V_n=100}*

The base fuel consumption neuron is described by (8) :

$$G_D = 410.33\exp\left(-\left|\frac{N-115.92}{51.89}\right|^{1.29} + -\left|\frac{P/D-127.03}{106.59}\right|\right) - 16.85 \qquad (8)$$

The mean absolute error of the fuel consumption base model is equal to 0.9211 at the maximum normalized value of 100. In the second step of modelling points of the maximum absolute error were found, the neurons placed into them and then the learning process with error samples was realized. In Fig.7 the base neuron and the first error neuron of the fuel consumption model is presented. Respective neurons of the speed model are of a similar form.



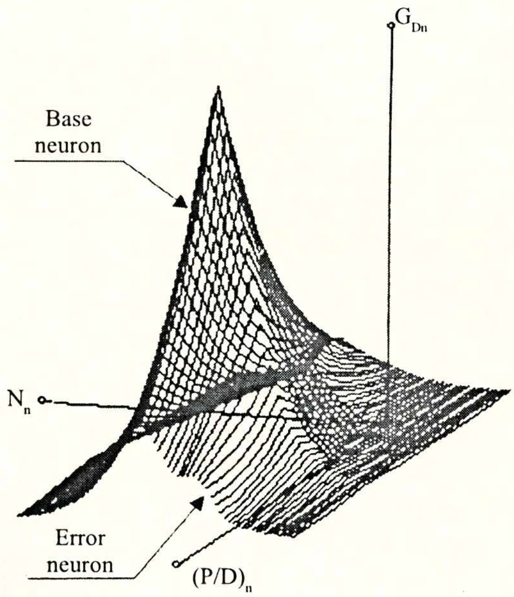


Fig.7. The base neuron and the first error neuron of the fuel consumption model {lengths of axis segments are : $(P/D)_n$=400, N_n=400, V_n=400}

The normalized fuel consumption model consisting of 2 neurons is given by (9) :

$$G_D = 410.33\exp\left(-\left|\frac{N-115.92}{51.89}\right|^{1.29} - \left|\frac{(P/D)_n-127.03}{106.59}\right|\right) +$$
$$-16.85 + 20.87\exp\left(-\left|\frac{0.98N+0.22(P/D)_n-109.72}{18.99}\right|^{3} + -\left|\frac{-0.22N+0.98(P/D)_n-32.19}{747.00}\right|^{7}\right) \qquad (9)$$

The mean absolute error of the model is equal to 0.4237.

The ship speed model with 2 neurons and its mean absolute error of 0.3971 are given by (10) :

$$V = 364.1\exp\left(-\left|\frac{0.97N+0.22(P/D)_n-111.04}{135.35}\right|^{1.64} + -\left|\frac{-0.22N+0.97(P/D)_n-85.68}{402.90}\right|^{1.62}\right) +$$
$$-231.94 + 18.14\exp\left(-\left|\frac{0.99N+0.12(P/D)_n-108.31}{20.43}\right|^{2.46} + -\left|\frac{-0.12N+0.99(P/D)_n-0.64}{18.34}\right|^{2.38}\right) \qquad (10)$$

In Fig.8 and 9 the trajectory of the optimum propulsion system settings $[N_n,(P/D)_{n,opt}]$ of the ship *Skulptor Konenkov* is shown, which was determined on the basis of the speed model (10) and the fuel consumption model (9) by applying the numerical search method.

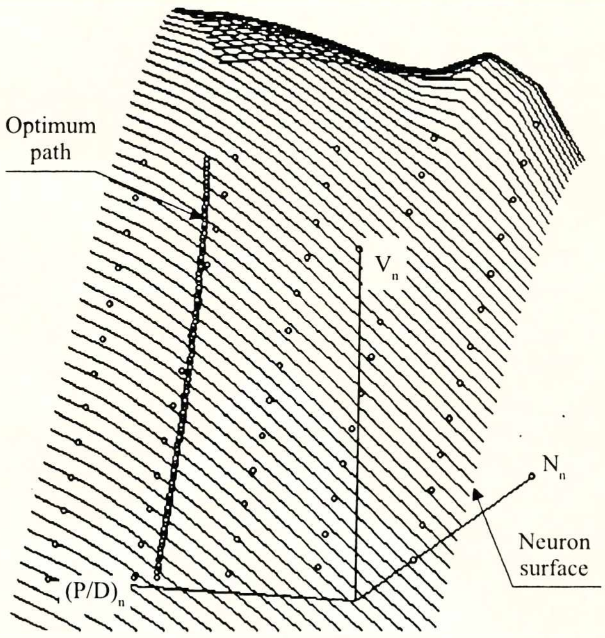


Fig.8. Path of the optimum settings of the normalized rotational propeller speed N_n and normalized pitch ratio $(P/D)_n$ of the ship Skulptor Konenkov, which minimize fuel consumption in the 3-dimensional space {V_n, N_n, $(P/D)_n$} {lengths of axis segments are : $(P/D)_n$=100, N_n=100, V_n=100}

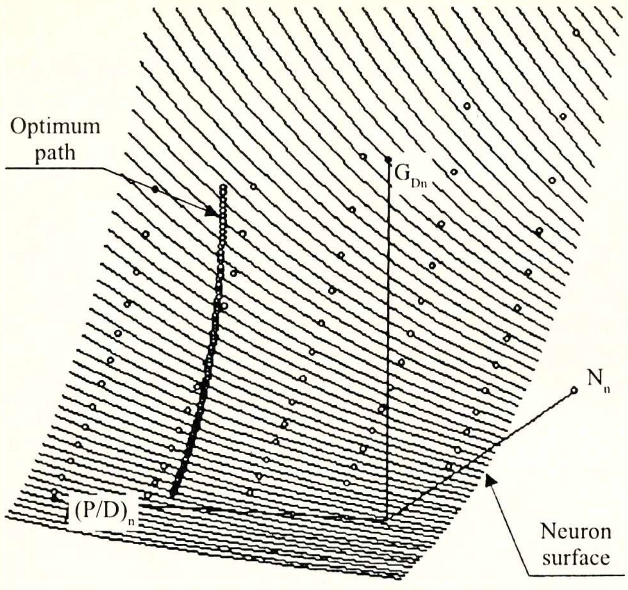


Fig.9. Path of the optimum settings of the normalized propeller speed N_n and normalized pitch ratio $(P/D)_n$ of the ship Skulptor Konenkov in the 3-dimensional space $[G_{Dn}, N_n, (P/D)_n]$ {lengths of axis segments are : $(P/D)_n = 100$, $N_n = 100$, $V_n = 100$}

The optimum settings are also presented in Tab.2, and in Fig.10 in the form of 2-dimensional diagram.

Tab.2. Optimum normalized settings of the propulsion system of the ship Skulptor Konenkov

V_n	0	1	2	...	98	99	100
$n_{n\,opt}$	7.192	7.643	8.152	...	56.228	56.789	82.685
$(P/D)_{n,opt}$	68.53	68.739	68.738	...	82.031	82.343	57.346
$G_{Dn,min}$	0.694	0.976	1.259	...	64.389	65.829	67.308

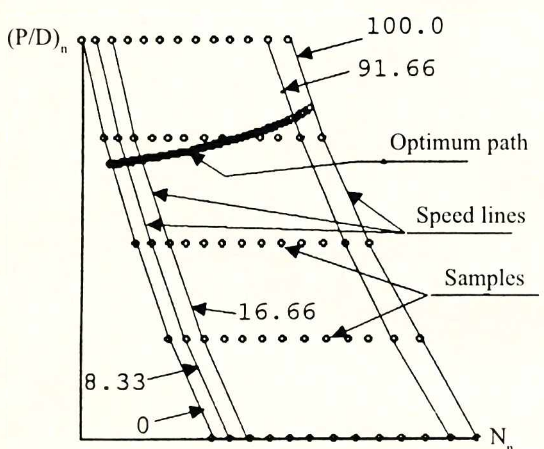


Fig.10. The optimum setting path which minimizes the fuel consumption of the ship Skulptor Konenkov in the 2-dimensional space $[(P/D)_n, N_n]$

Due to the normalized character of the model variables the normalized speed $V_n = 0$ does not mean zero-dimensional speed of the ship but the smallest speed (expressed in knots) which appears in the measurement samples used for identification. The same refers to the normalized fuel consumption zero-value. Neural modelling with the use of the residua method can theoretically be continued till the mean absolute error reaches zero-value. However, in practice the neural network with zero-error would model the disturbances and noises caused by varying ship operating conditions and measurement noises. Such situation is called the *overlearning* of neural networks [8,9]. The overlearned networks calculate often senseless output values and hence cannot be used. Therefore learning of a neural network should be stopped at a certain error value which is greater than zero but satisfactorily small.

CONCLUSIONS

- The presented neural modelling method makes it possible to model the CPP-propulsion system with an arbitrary accuracy depending only on the disturbance and noise level of measurement samples.
- The network structure (number of neurons in the hidden layer) depends on the required modelling accuracy.
- The experimental modelling of the propulsion system of the ship *Skulptor Konenkov* confirmed the advantages of network.
- In the course of modelling the optimum setting path which minimizes the fuel consumption was obtained.
- The error residua learning method can also be applied to modelling other causalities of the ship propulsion system, e.g. stabilization of the engine power at the maximum efficiency point of the engine-CPP propulsion system.

NOMENCLATURE

a_0 - altitude of the base neuron
b_0 - height of the base neuron
b_{0M} - height of the error E_0 neuron
d - disturbances influencing the hull resistance
d_1 - disturbances influencing engine operations as e.g. fuel calorific value
d_2 - disturbances influencing the propeller thrust as e.g. draught
d_3 - disturbances influencing the hull resistance as e.g. current, waves, wind, etc.
D - propeller diameter
e_0 - base model error value
E_0 - error of the base model M_0
e_{0M} - output of the base model error
E_{0M} - general symbol of the error E_0 of the base model M_0
e_1 - output of the first error residuum
E_1 - general symbol of the first error residuum
E_{1M} - general symbol of the first error residuum model
E_2 - general symbol of the second error residuum
g_i - coefficients
G_D - fuel consumption
h - fuel rack setting
J - advance coefficient of the propeller
K_T - thrust coefficient
l_{j0} - power exponent of the base neuron component in the x_j/y plane
l_{j0M} - power exponent of the error E_0 neuron component in the x_j/y plane
M - engine load torque
M_0 - base model of the system
M_d - additional load torque on the engine shaft caused by other power receivers on the ship
m_{j0} - co-ordinate of the base neuron centre along the x_j axis
m_{j0M} - co-ordinate of the error E_0 neuron centre along the x_j axis
N - rotational propeller speed
N_n - propeller rotational speed normalised to interval (0,100)
N_c - commanded rotational propeller speed
P - pitch of the propeller
P/D - pitch ratio
$(P/D)_c$ - commanded pitch ratio
$(P/D)_n$ - pitch ratio normalised to interval (0,100)
Q - propeller resistance torque
S - surface of the $X \rightarrow Y$ (inputs→output) mapping of the modelled system
R - hull resistance
RBF - radial basis function
T - propeller thrust
V - geographical ship speed
V_n - ship speed normalised to interval [0,100]
y_0 - output of the base model M_0
δ_{j0} - width of the base neuron component in the x_j/y plane
δ_{j0M} - width of the error E_0 neuron component in the x_j/y plane
ς - water density
$|...|$ - sign of absolute value

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Conference

BEARING TECHNOLOGY '99 DIAGNOSTICS OF BEARINGS

On 19÷21 May 1999 a scientific technical conference under this heading was held in Sopot. For the first time it encompassed all bearing technology problems, i.e. apart from construction, research and exploitation topics it also comprised bearing diagnostics themes. The conference was organized by as many as 7 leading scientific institutions headed by the Mechanical Engineering Committee, Polish Academy of Sciences.

Apart from its topical problems the conference was devoted to celebrating the 50th anniversary of scientific research activity of Prof. Bolesław Wojciechowicz, the man of merit as a scientific worker, academic teacher, organizer and tutor of many young scientists and experts.

About 150 conference participants from different universities, scientific research institutes and industry had an opportunity to hear and discuss 30 papers presented during the solemn session and 7 working ones.

Many occasional speeches made during the solemn session were supplemented by two following papers :

- „Exploitation science and bearing technology yesterday, today and tomorrow" presented by Prof.B.Wojciechowicz
- „Abrasive wear in the light of the research work of the scientific school of Prof. Bolesław Wojciechowicz" by W.Leszek and W.Zwierzycki

In the remaining 28 papers very wide scope of topics was presented which could be classified as follows :

- The state and development prospects of tribology and trends in developing the unattended bearings
- Material and microstructural aspects of tribological processes
- Bearing surface forming technique
- Bearing dynamic processes
- Investigation of bearing strength and durability
- Special bearing design and construction problems
- Special bearing characteristics and research
- Diagnostics and computer analysis applied to bearing technology
- Bearing failure diagnostics by using the vibroacoustic method
- Thermal diagnostics of friction units

30 more papers were presented during poster sessions. One of them, called „industrial session" was specially organized for industry representatives where peculiar properties of double-surface hydrodynamic bearings and of novel antivibration bearings, as well as construction problems of axial bearings of the reversible hydro-units were presented.

The sight-seeing tour onboard a naval vessel around Gdynia port was unquestionably attractive for its participants.

Miscellanea

Main Library of the Technical University of Gdańsk

Main Library, Technical University of Gdańsk is the oldest and greatest collection of technical books and publications in North Poland. It was established in 1904. Size of the collection grew fast from 30 thousand volumes in 1910 to 150 thousand in 1944. Provenience of its old print collection is determined as that of the first half of XVII century. These are mainly collections of Naturalist Society in Gdańsk, whose origins go back to 1743. They consisted of over 30 000 volumes dealing with natural sciences and mathematics, history, geography, medicine, inclusive of very valuable cimelia of the humanities.

In 1923 this precious collection was handed over by Naturalist Society to Technical University of Gdańsk.

The years of World War II were cruel to the Library collection. It was not saved from fire, water, looting and inevitable deterioration due to passing time.

The few saved collections formed the origin of the contemporary Main Library, Technical University of Gdańsk.

The Main Library, as the central information – library system of the University, owns over 1.2 million volumes collected not only for needs of education and science, but also for wide needs of Polish maritime economy. The Library, having 12 reading rooms and lending room, serves more than 900 thousand readers per year, makes 4000 books and 2100 volumes of journals, standard and patent publications available per day. It has 32 000 permanent readers registered in a computer system.

The data base on the scientific research carried out at the Technical University of Gdańsk consists of 47 000 records which can be currently accessed through a computer network.

The Library also carries out didactic and scientific activity, apart from the everyday tasks, carrying out promotion activity of the University by organizing exhibitions, as well as undertaking projects on information technique improvement.

For eight years, the problems of automation and computerization of scientific information have been a leading aim of the Library's activity. In result a computer aided information system was elaborated and implemented which greatly improved quality of the Library operations. This computer aided information system APIS is considered competitive to similar foreign systems. It fully covers the essential and service activity of the Library, moreover, it makes many operations connected with functioning of the library services more effective. The system operates within the overall computer network of the University as well as it is accessible through the Three-Town Academic Computer Network and Internet.

Realization of the TEMPUS JEP+ project nr 7853 (with co--authorship of the Library) is an undertaking of equal importance for development of a national scientific information system.

The Library also elaborated and realized a project on computerization of scientific information directed to Soros Foundation. The project consisted in purchasing the computer equipment and software to make CD-ROM data bases available from a computer network. The Library has co-ordinated realization of the entire project.

The Library accepted the proposal to be a co-ordinator of the project on purchase and implementation of the newest version of VLTS-VIRTUA, on American computer information system intended to substitute the older VLTS version earlier installed in some Polish libraries. An attempt was already made to acquire a licence on using the system by Technical University of Gdańsk and 8 remaining scientific libraries of Three-Town.

The Library co-operates with 77 greatest libraries and scientific information centres from 26 countries. The entire scope of activities carried out by the Main Library of the Technical University of Gdańsk introduces it to the group of the scientific libraries of importance in Poland and Europe.