Aeroengine NOx-emissions automatic control based on neural network model

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The adaptive optimal NOx-emission control is the most important problems for aeroengine automatic control systems design because the aeroengine harmful emissions must comply with the ICAO international standards.
The critical unit of the engine in terms of harmful emission generation is the combustion chamber.
The main problems of an NOx-automatic control are:

1. The impossibility of the direct measurements of the main engine physical parameters during the flight.
2. The essentially stochasticity and non-linearity of the combustion chamber makes it difficult to identify its characteristics by usual analytic methods.

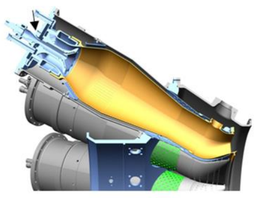
For solving this problem the developing of built-in neural network model of combustion chamber is offered.

Controlling algorithm is based on the pilot fuel ratio (PFR) optimizing
As the an aircraft gas turbine engine's combustion chamber is a complex stochastic system, the use of analytical controlling methods is difficult. So, the use of nonlinear programming methods is proposed.
The universal method of Monte-Carlo statistical modeling was chosen.

The accuracy of the numerical method of Monte-Carlo is determined by the quality of the random number generator used in the control algorithm.
The quality of the random number generator depends on uniformity of the distribution density and the non-correlation of the analyzed random points inside the multidimensional cube limiting the space of acceptable change of the optimized parameters.
Therefore, the influence of quality of pseudo-random sequences on control accuracy is analyzed in this study.

THE BUILT-IN NEURAL NETWORK MODEL OF COMBUSTION CHAMBER DEVELOPMENT

A predictive built-in model for calculation (estimation) of the NOx emissions level, allowing determining the optimal value of pilot fuel ratio (PFR), is designed by neural network technology



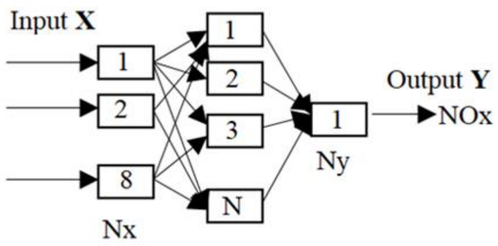
The industrial combustion chamber

THE CHOICE OF NEURAL NETWORK PARAMETERS: INPUT AND OUTPUT SIGNALS

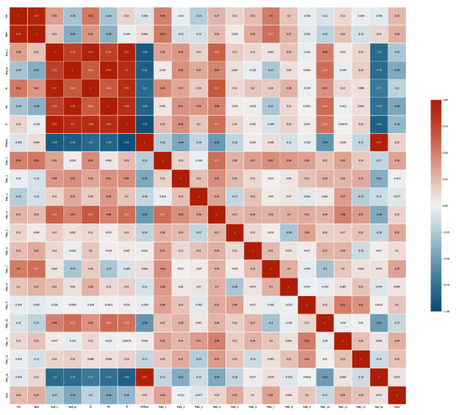
In the neural network simulation of the emission of nitrogen oxides, the eight input signals were chosen as the coordinates of the extended input vector of the low-emission combustion chamber $\mathbf{X}\{x_1 \dots x_8\}$:

- inlet temperature (outlet of engine inlet device) T_{inlet};
- atmospheric temperature (overboard) T_{atm},
- gas generator rotor speed N_{gg};
- corrected gas generator rotor speed $N_{gg\ cor}$;
- high pressure compressor outlet pressure P_c;
- high pressure compressor outlet temperature T_c;
- turbine outlet temperature T_T;
- pilot fuel ratio (PFR).

The output of the model $\mathbf{Y}(y_1)$ is NOx emissions level.



COEFFICIENTS BETWEEN THE INPUT AND OUTPUT SIGNALS OF THE COMBUSTION CHAMBER



The calculation of the correlation of input and output data is based on the definition of a simple Pearson correlation coefficient

$$r = \frac{1}{n\sigma_x\sigma_y}\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})$$

$$\sigma_x = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^2}$$

$$\sigma_y = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i-\bar{y})^2}$$

THE CHOICE OF NEURAL NETWORK PARAMETERS

The calculation of the neural network parameters was estimated due to the corollary from the Kolmogorov–Arnold–Hecht–Nielsen (KAHN) theorem:

- the number of synaptic weights

$$\frac{N_y N_p}{1+\log_2(N_p)} \le N_w \le \le \left(\frac{N_y N_p}{N_x}+N_y\right)(N_x+N_y+1)+N_y$$

where N_x, N_y are the dimensions of the input (output) signal vector; N_p is the number of elements of the training sample; N_w is the required number of synaptic weights.

- the number of neurons in the hidden layer is:

$$N = \frac{N_w}{N_x+N_y}$$

The resulting number of neurons in the hidden layer was refined by the empirical formula:

$$\frac{N_x}{2} \le N \le (3 \div 5)\cdot N_x$$

In this work, it was proposed to simulate NOx emission using a two-layer fully connected neural network with direct signal transmission.

When designing the model, we had an array of experimental data with the dimension N_p =578.

The First Neural Network NOx model:

- The number of inputs of neural network (NN) was reduced to $N_x = 8$.
- The required integer number of synaptic connections for $N_x = 8$, N_y =1, N_p =578 is $57 \le N_w \le 734$,
- The number of neurons in the hidden layer is:

$$7 \le N \le 82 \text{ or } 4 \le N \le (24 \div 40)$$

The analysis of the Pearson correlation coefficients between given input and output signals proved a low correlation of the atmospheric temperature and inlet temperature with the level of NOx emission.

NOx, mg/m3	Tinlet, °C	Tatm °C	Ngg, rpm	Ngg cor, rpm	T_c °C	P_c, kgf/cm2	Fair cc, kg/s	Tt °C	PFR
	-0.059	0.13	-0.8	-0.78	-0.71	-0.76	-0.86	0.97	

The Pearson correlation coefficients between given input and output signals

The Second Neural Network NOx model:

- The number of inputs of neural network (NN) was reduced to $N_x = 6$.
- The required integer number of synaptic connections for $N_x = 6$, N_y =1, N_p =578 is $57 \le N_w \le 780$,
- The number of neurons in the hidden layer is:

$$9 \le N \le 112 \text{ or } 3 \le N \le (18 \div 30)$$

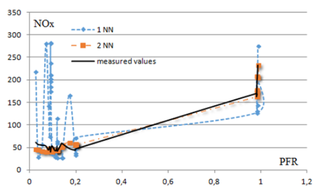
COMPARATIVE MATLAB R2018B ANALYSIS OF THE NEURAL NETWORKS (NN) ACCURACY

Comparative MATLAB R2018b analysis of the accuracy of neural networks (NN) with the different number of inputs and neurons in the hidden layer with different training algorithm, developed for the assembly of the aeroengine low-emission combustion chamber 25 MW with the training sample dimension Np= 578 and testing and estimating sample dimension Ntest+estim= 35 is shown in Table 1.

The analysis shows that the second neural network NN 2 has a higher accuracy of NOx emission modeling, respectively: for the testing sample in 17.974 times, for the predictive sample in 2.426 times

TABLE I. THE ANALYSIS OF THE ACCURACY OF NEURAL NETWORKS WITH DIFFERENT NUMBERS OF INPUTS AND NEURONS IN THE HIDDEN LAYER

NN	N_x	N	Training algorithm	The relative error of built-in model, %	
				Test	*Validation*
1NN	8	30	Bayesian	215.5362	11.99152
2NN	6	11	Levenberg-Marquardt	42.21505	17.40188



The graph of the change in the relative error on the training, testing and predictive samples for two neural network models

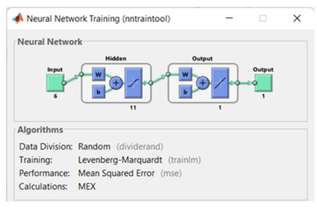
THE NEURAL NETWORK MODEL EXPERIMENTAL TESTING

The analysis results of experiments with the 1 NN model showed that the maximum emissions of nitrogen oxides level are observed at low PFRs in the operating range PFR∈[0; 0.2], and their maximum value reaches 266.823 mg/m3. This exceeds the allowable set value in 5.72 times.

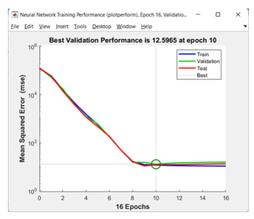
While for the 2 NN model on this range PFR∈[0; 0.2] the average relative error is 15.628%, and the maximum relative error is 36.465%. This is 15 times less than for the 1 NN model.

The emissions of nitrogen oxides level in the remaining range of change PFR∈[0.2; 1] also shows the best quality of the 2 NN model. The average relative error for 1 NN is 22,054%, and the average relative error for 2 NN is 5,237%. This is 4.21 times less.

Thus, in the further development of the automatic control system of the emission of nitrogen oxides from the combustion chamber of an aeroengine, the second model 2 NN was used.



The structure of the second neural network model 2 NN demonstrating the greater modeling accuracy



The graph of the change in the mean square error on the training, test and predictive samples by training epochs for the second neural network model 2 NN

THE MONTE CARLO OPTIMIZATION ALGORITHM DETERMINATION OF PROBABILITY DISTRIBUTIONS OF VARIABLES IN SEARCH AREA

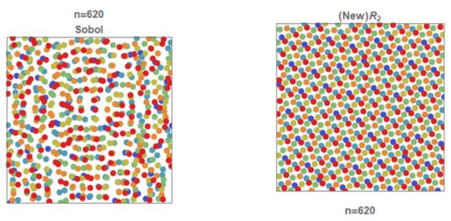
When applying numerical programming methods in the cube V choose N random points x_i.

The values of any random variable distributed according to some law can be obtained by converting the values of one of any "standard" random variable. As a rule, the role of the "standard" value is played by a random variable ξ uniformly distributed in the range $\xi \in [0;1]$.

The optimal solution assumes that random points x_i have a uniform distribution density in the cube of V and are not correlated. Strict mathematical methods for constructing such points have not been found. A number of mathematical algorithms for obtaining non-random (pseudo-random/quasi-random) sequences implemented as random number generators are proposed.

Such sequences are simulated by sets of pseudo-random/quasi-random numbers ξ_j calculated using some mathematical formulas (in most cases, heuristic). Any proposed algorithm is tested to check the feasibility of the properties characteristic of random uniformly distributed sequences, in particular, how uniformly the points corresponding to ξ_j are distributed in cubes of different dimensions.

Among non-random sequences, pseudo-random and quasi-random sequences should be distinguished.
A sequence of nonrandom numbers is called pseudorandom if it has all the properties of a random sequence.
A sequence of non-random numbers is called quasi-random if it can be used in Monte Carlo methods instead of random.

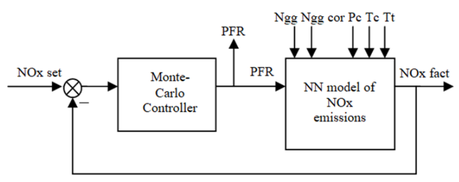


The visual analyze of the distribution of projections of points onto two-dimensional areas for Sobol and Kronecker sequences

THE NOx EMISSIONS CONTROL SYSTEM TESTING

The study solves the problem of automatic control of the emission of nitrogen oxides from the aeroengine combustion chamber.
Controlling algorithm, implementing in *Python*, is based on the pilot fuel ratio (PFR) optimizing.
Since direct measurement of NOx emissions in flight is not available, the control system uses a built-in neural network (NN) model of generating emissions prediction. An experimental comparative analysis of the control accuracy for the best developed model 2 NN was carried out.
The automatic control is implemented in a closed loop with use of the principle of regulation by deviation of the *NOx* emissions level (mg/m^3) from the set value NOx_{set}. The optimization criterion was

$$min\ F = \int |NO_{X\,set} - NO_X|\, dt$$



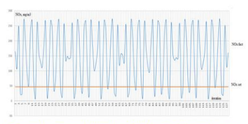
The block diagram of the automatic control system of NOx emissions

THE CONTROL ACCURACY OF AUTOMATIC CONTROL SYSTEM WITH VIRTUAL SENSOR OF NOx EMISSIONS BASED ON THE SOBOL SEQUENCE

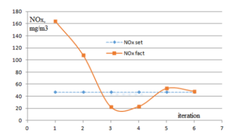
The analysis of the influence of quality of quasi-random Sobol sequence on the control accuracy of Automatic Control System with virtual sensor of NOx emissions based on 2 NN for different number of iterations shows:

overshoot (maximum release above the set value of the NOx emission level) is 251.53%,

transient time is 5.5 iterations.



The control accuracy of Automatic Control System with virtual sensor of NOx emissions based on built-in neural network model 2 NN with Sobol sequence random number generator



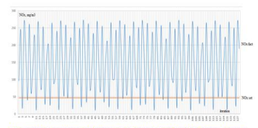
The control accuracy of Automatic Control System with virtual sensor of NOx emissions based on built-in neural network model 2 NN with Sobol sequence random number generator for the most close to the NOxset = 46.6% while fitting the optimal PFR

THE CONTROL ACCURACY OF AUTOMATIC CONTROL SYSTEM WITH VIRTUAL SENSOR OF NOx EMISSIONS BASED ON THE KRONECKER SEQUENCE

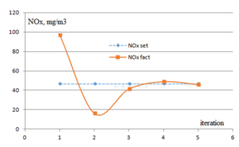
The analysis of the influence of quality of quasi-random Kronecker sequence (using the golden ratio random number generator) on the control accuracy of Automatic Control System with virtual sensor of NOx emissions based on 2 NN for different number of iterations shows:

overshoot (maximum release above the set value of the NOx emission level) is 107.19%,

transient time is 3.5 iterations.



The control accuracy of Automatic Control System with virtual sensor of NOx emissions based on built-in neural network model 2 NN with Kronecker sequence random number generator



The control accuracy of Automatic Control System with virtual sensor of NOx emissions based on built-in neural network model 2 NN with Kronecker sequence random number generator for the most close to the NOxset = 46.6% while fitting the optimal PFR

References:

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3. T.A. Kuznetsova, "Some features of quality improvement of a neural network identifying a aeroengine low-emission combustion chamber," Proceedings of IEEE 3rd International Conference on Control Systems, Mathematical Modeling, Automation and Energy Efficiency (SUMMA-2021), Nov. 10-12, Lipetsk, Russian Federation, 2021. DOI 10.1109/SUMMA53307.2021.9632262