Air debit's automatic regulation in the aircrafts' cabins using a debit regulator with direct action

Romulus Lungu, Constantin Rotaru, Alexandru Tudosie, Adrian Stanciu

Abstract— The paper presents the mathematical model of a system, with direct action, for the regulation of the air debit in the aircrafts' cabins. It consists of a debit transducer, a regulator and an execution element. Using two different methods (least square method and neural networks method), one makes the identification of the system, obtaining (using a Matlab program and a Matlab/Simulink model) the responses to step or impulse input in the complex and discrete planes and time variations of non-dimensional pressure inside the regulator. With least square method (LSM) the output of the system and the output of the model were plotted. The identification is made very well – the two signals overlap. The identification may also be made using neural networks. Using this method, one obtained the indicial responses of the control system and of the neural network before and after the training process.

Keywords— regulator, air debit, aircraft' cabin, transducer, execution element.

I. Introduction

The automatic regulation of the air debit which enters in aircrafts' cabins has the following purposes: the expanding of the air mass that flows through the valve of the pressure control system (ARS) through leaks; the ensure of the cabin air pressure regulation [1], [2], [3].

In this paper one presents the mathematical model of the air debit automatic regulation system (ARS) consisting of debit transducer, regulator and execution element. For this system (system with direct action) one obtains the mathematical model which permits its description in a dimensional, non-dimensional or operational form. The study of the system refers to its stability and identification using different identification methods.

The term *pressurization* means the process of creation of a extra-pressure in the hermetically aircrafts' cabins [1], [2], [3]. The air debit introduced in the cabin for one person is about $20 \div 30\,\mathrm{m^3/h}$; the CO_2 concentration must not exceed $0.5 \div 1\%$, while the temperature must be $20 \div 25^\circ C$.

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II. Structure of the pressure control system (ARS)

This system is presented in fig.1. The components of the system are: 1 – fixed cylinder; 2 – mobile cylinder with valve; 3 – Venturi nozzle (tube); 4 – shell; 5 – spring; 6 – goffering box; 7 – safety valve [1], [2], [3], [4].

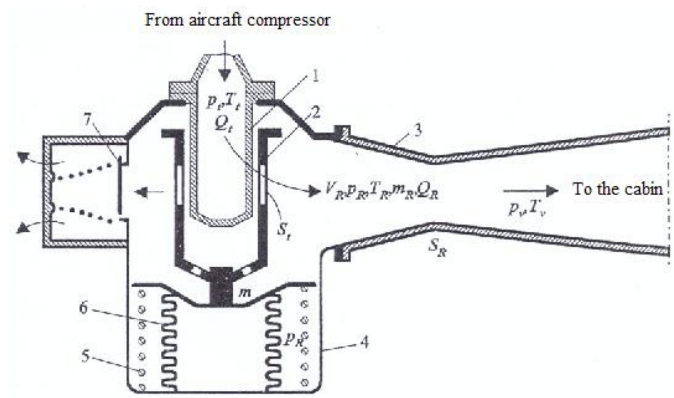

Fig.1 The structure of the debit (pressure) control system

On the lateral surface of the fixed cylinder there are shaped orifices. These are opturated more or less in rapport with the mobile cylinder's position and with valve 2. The valve is moved by the mean of elements 5 and 6. In the case of the pressure's increase over a prescribed maximum value, the air is evacuated in the atmosphere through the safe valve 7.

III. The mathematical model and the stability analysys of the pressure control system

The system presented in fig.1 maintains constant the pressure p_R in the room of the regulator, limiting the air debit transmitted to the cabin.

The dynamic regime of the regulator is described by equation [1], [2], [3], [4]

$$\frac{V_R}{RT_R^0}\frac{\mathrm{d}}{\mathrm{d}t}\Delta P_R + \left(\frac{\partial Q_R}{\partial p_R} - \frac{\partial Q_t}{\partial p_R}\right)_0 \Delta P_R = \left(\frac{\partial Q_t}{\partial p_t}\right)_0 \Delta p_t - \\ - \left(\frac{\partial Q_t}{\partial p_v}\right)_0 \Delta p_v + \left(\frac{\partial Q_t}{\partial T_t}\right)_0 \Delta T_t - \left(\frac{\partial Q_R}{\partial T_R}\right)_0 \Delta T_R + \left(\frac{\partial Q_t}{\partial S_t}\right)_0 \Delta S_t, \quad (1)$$

where Q_t is the air debit from the aircraft's compressor,

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Q_R – the debit which goes to the cabin, p_t, p_R, p_v – pressures in different parts of the regulator, T_t, T_R – temperatures in different parts of the regulator, S_t – the variable section of air flow through the regulator.

Using the non-dimensional notations

$$\begin{aligned}&\bar{p}_R = \frac{\Delta p_R}{p_N}, \bar{p}_t = \frac{\Delta p_t}{p_N}, \bar{p}_v = \frac{\Delta p_v}{p_N}, q_R = \frac{\Delta Q_R}{Q_{t_{\max}}},\\ &q_t = \frac{\Delta Q_t}{Q_{t_{\max}}}, \theta_t = \frac{\Delta T_t}{T_{t_{\max}}}, \theta_R = \frac{\Delta T_R}{T_{R_{\max}}}, \bar{S}_t = \frac{\Delta S_t}{S_{t_{\max}}},\end{aligned} \tag{2}$$

one obtains the non-dimensional form of equation (1)

$$\begin{aligned}&\tau_R^* \frac{d\bar{p}_R}{dt} + k_R \bar{p}_R = \frac{\partial q_t}{\partial \bar{p}_t}\bar{p}_t - \frac{\partial q_R}{\partial \bar{p}_v}\bar{p}_v + \frac{\partial q_t}{\partial \theta_t}\theta_t - \\ &- \frac{\partial q_t}{\partial \theta_R}\theta_R + \frac{\partial q_t}{\partial S_t} S_t,\end{aligned} \tag{3}$$

with the notations: $\tau_R^* = \frac{V_R p_N}{R T_R^0 Q_{t_{\max}}}$ – the filling time of the regulator's room, $k_R = \frac{\partial q_R}{\partial \bar{p}_R} - \frac{\partial q_t}{\partial \bar{p}_R}$ – the coefficient of auto-equalization of the regulation element's pressures (all the brackets with index "0" have been neglected).

In stationary regime, the valve of the debit regulator has an equilibrium position expressed by the mean of coordinate x_0 (x is the displacement of cylinder 2; it is considered positive when it moves down). The equilibrium of the forces for the mobile elements of mass m is expressed by equation [1], [2]

$$m\frac{d^2\Delta x}{dt^2} + \eta\frac{d\Delta x}{dt} + k_e \Delta x + F_f = S_{ef}\Delta p_R, \tag{4}$$

where k_e is the elasticity coefficient of the spring, η – the damping friction coefficient, F_f – the friction force and S_{ef} – the effective surface of the goffering box.

Neglecting the friction force F_f and using the non-dimensional variable

$$\bar{x} = \frac{\Delta x}{x_{\max}} = -\frac{\Delta S_t}{S_{t_{\max}}} = -\bar{S}_t, \tag{5}$$

one yields the equation in a non-dimensional form

$$\tau_m^2 \frac{d^2\bar{S}_t}{dt^2} + 2\xi_m \tau_m \frac{d\bar{S}_t}{dt} + \bar{S}_t = -k\bar{p}_R, \tag{6}$$

where one used the notations

$$\tau_m^2 = \frac{m}{k_e}; 2\xi_m\tau_m = \frac{\eta}{k_e}; k = \frac{S_{ef} p_N}{k_e x_{\max}}. \tag{7}$$

Starting from equation (3) and using notation

$$\begin{aligned}&\frac{\partial q_t}{\partial \bar{p}_t}\bar{p}_t - \frac{\partial q_R}{\partial \bar{p}_v}\bar{p}_v + \frac{\partial q_t}{\partial \theta_t}\theta_t - \frac{\partial q_t}{\partial \theta_R}\theta_R = F(t);\\ &\frac{\partial q_t}{\partial \bar{S}_t} = k_t,\end{aligned} \tag{8}$$

equations (3) and (6) become

$$\begin{aligned}&\tau_R \frac{d\bar{p}_R}{dt} + \bar{p}_R - k_t \bar{S}_t = \frac{F(t)}{k_R},\\ &\tau_m^2 \frac{d^2\bar{S}_t}{dt^2} + 2\xi_m\tau_m \frac{d\bar{S}_t}{dt} + \bar{S}_t = -k\bar{p}_R,\end{aligned} \tag{9}$$

where $\tau_R = \tau_R^* / k_R$ – time constant.

Using Laplace transformation for the two above equations, and after that eliminating variable $\bar{S}(s)$, one gets

$$\begin{aligned}&\left(a_3 s^3 + a_2 s^2 + a_1 s + a_0\right)\bar{p}_R(s) = \left(\tau_m^2 s^2 + 2\xi_m\tau_m s + 1\right)F(s)\\ &\Leftrightarrow H(s) = \frac{\bar{p}_R(s)}{F(s)} = \frac{\tau_m^2 s^2 + 2\xi_m\tau_m s + 1}{a_3 s^3 + a_2 s^2 + a_1 s + a_0},\end{aligned} \tag{10}$$

where

$$\begin{aligned}&a_3 = k_R \tau_R \tau_m^2, a_2 = k_R\left(2\xi_m\tau_m\tau_R + \tau_m^2\right),\\ &a_1 = k_R\left(\tau_R + 2\xi_m\tau_m\right), a_0 = k_R + k k_t.\end{aligned} \tag{11}$$

The characteristic equation of the system is

$$a_3 s^3 + a_2 s^2 + a_1 s + a_0 = 0 \tag{12}$$

and the Hurwitz stability equations are expressed by the positivity of coefficients $a_i, i = \overline{0,3}$ – true condition and by the inequality $a_1 a_2 > a_0 a_3$, which, conform to (11), becomes

$$k_R\left(\tau_R + 2\xi_m\tau_m\right)\left(2\xi_m\tau_R + \tau_m\right) > \tau_R\tau_m\left(k_R + k k_t\right). \tag{13}$$

In fig.2 [3], [4] one presents the block diagram of the model described by equations (9).

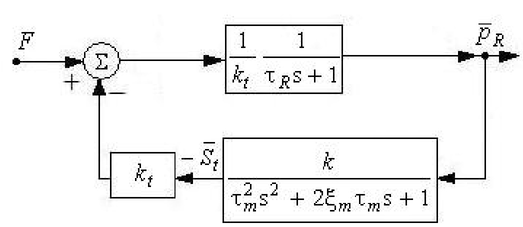

Fig.2 The block diagram of the system's model

For $Q_{t_{\max}} = 0.02\,\text{kg/s}, T_R = 300\,\text{K}, V_R = 10^{-1}\,\text{m}^3, p_N = 10^5\,\text{N/m}^2$, one obtains $\tau_R^* = 5.8\text{s}$. With $\Delta Q_R / Q_{t\max} = 4 \cdot 10^{-3}$, $\Delta Q_t / Q_{t\max} = -6 \cdot 10^{-3}, \Delta p_R / p_N = 10^{-5}$, it results $k_R = 10^3$

and $\tau_R = \tau_R^* / k_R = 5.8 \cdot 10^{-3}$ s. The coefficient k_t is calculated from the second equation (8); for $\Delta x / x_{\max} = 0.1$ and $\Delta Q_t / Q_{t_{\max}} = -6 \cdot 10^{-3}$, one gets $k_t = 6 \cdot 10^{-2}$.

With

$$
\begin{aligned}
&m = 1\,\text{kg}, k_e = 1\,\text{N/m}, \eta = 0.32\,\text{Ns/m},\\
&x_{\max} = 0.015\,\text{m}, S_{ef} = 3 \cdot 10^{-3}\,\text{m}^2
\end{aligned}
\tag{14}
$$

using (6), one obtains $\tau_m = 1, \xi_m = 0.16, k = 2 \cdot 10^4$.

The value of the perturbation $F(t)$ is calculated first equation (8). It results $F(t) = 2 \cdot 10^{-3}$.

Using the Matlab/Simulink model (fig.3) of the block diagram from fig.2, one obtains the time variations of the non-dimensional pressure inside the regulator – fig.4.

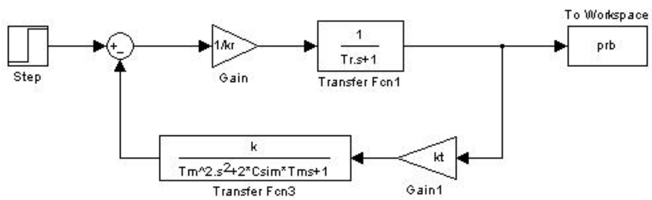

Fig.3 The Matlab/Simulink model of the ARS

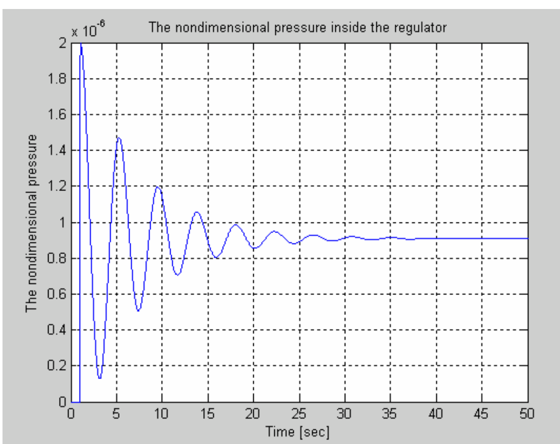

Fig.4 Time variation of the non-dimensional pressure $\bar{p}_R$ inside the regulator

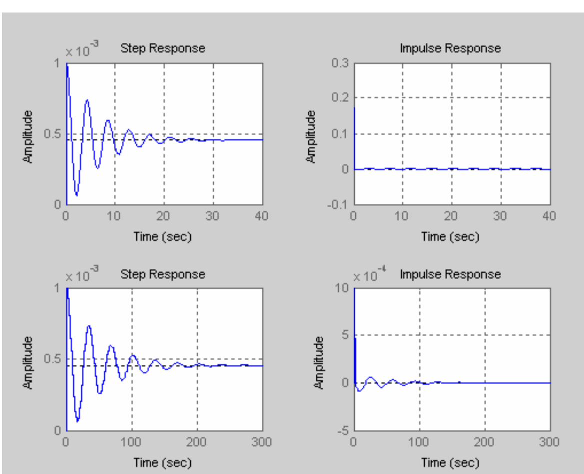

Fig.5 The indicial functions and responses to impulse input in the complex and discrete planes for the system from fig.2

For the above system one also obtains, using a Matlab program and a Simulink model (fig.3), the frequency characteristics, the indicial functions in the complex plane and in discrete plane, responses to impulse input in the complex and discrete planes. Also, one identifies the systems using two different methods (least square method, and neural networks method). For each of these methods, some graphics were obtained. For the system from fig.2, the indicial functions and responses to impulse input in the complex and discrete planes are presented in fig.5 (the first two graphics correspond to the complex plane, while the last two correspond to the discrete plane).

The program also calculates the matrices that describe the state equations of the system in the complex or discrete plane

$$
\begin{aligned}
&A = \begin{bmatrix} -172.73 & 56.17 & -379.31 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}; B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix};\\
&C = [0.1724 \;\; 0.0552 \;\; 0.1724]; D = [0];\\
&A\_z = \begin{bmatrix} 1.92 & -0.96 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}; B\_z = B;\\
&C\_z = [0.001 \;\; -0.0019 \;\; 0.001]; D\_z = D,
\end{aligned}
\tag{15}
$$

the poles of the system

$$
\begin{aligned}
p_1 &= -172.42;\\
p_2 &= -0.16 + 1.47\mathrm{i};\\
p_3 &= -0.16 - 1.47\mathrm{i};
\end{aligned}
\tag{16}
$$

the zeros, the transfer functions in complex description or in discrete description, the stability margins and so on.

From graphic characteristics – fig.4, fig.5 and from the analysis of the system's eigenvalues (poles) one notices that the system is a stable one with good dynamic properties.

IV. Identification of the System Using the Least Square Method (LSM)

A state estimator must assure the controllability of the system whose parameters are estimated, whatever the adaptive structure [5], [6]. The least square method doesn't always give models characterized by controllability. That's why in some cases it must be modified. The system A and the estimated model of the system $\hat{A}$ are described by the equations

$$
\begin{aligned}
L(z^{-1})y(t) &= z^{-q}M(z^{-1})u(t) + C(z^{-1})e(t) + d,\\
\hat{L}(z^{-1})y(t) &= z^{-q}\hat{M}(z^{-1})u(t) + \hat{C}(z^{-1})\hat{e}(t) + d,
\end{aligned}
\tag{17}
$$

where z^{-1} – the delay operator, $L(z^{-1})$ and $M(z^{-1})$ are polynomials containing the coefficients of the discrete transfer function, $\hat{e}(t)$ is the noise applied to the model and polynomials $\hat{L}(z^{-1}), \hat{M}(z^{-1})$ contain the estimated coeffici-

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ents of $L(z^{-1})$ and $M(z^{-1})$.

LSM algorithm (least square algorithm) modification is based upon the discrete transfer function modification through origin pole $(z = 0)$ compensation. The modified LSM algorithm (LSMM) builds a convergent vector $\nu(t)$ and with it the vector of the estimated parameters [7], [8]

$$\hat{b}'(k) = \hat{b}(k) + P(k)\nu(k). \tag{18}$$

Thus, the coefficient $\hat{b}'$ is almost non-null.

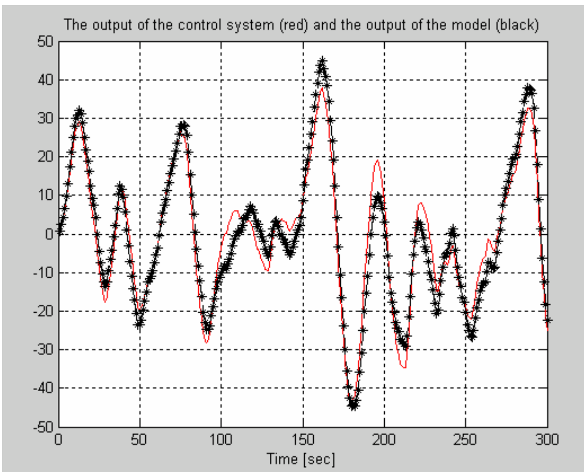

Fig.6 The debit control system's output and the model's output

The control law may be chosen of general form

$$u(k) = R\left(z^{-1}, \hat{b}'\right)u(k) + S\left(z^{-1}, \hat{b}'\right)y(k), \tag{19}$$

with the polynomials

$$R\left(z^{-1}, \hat{b}'\right) = \sum_{i=1}^{\alpha} z^{-i} r_i(\hat{b}') \text{ , } S\left(z^{-1}, \hat{b}'\right) = \sum_{i=0}^{\beta} z^{-i} s_i(\hat{b}'). \tag{20}$$

The closed loop system is described by equation [7]

$$W(k+1) = D\left(z^{-1}, \hat{b}'\right)W(k) + \begin{bmatrix} e(k+1) \\ 0 \end{bmatrix}, \tag{21}$$

where

$$D\left(z^{-1}, \hat{b}'\right) = \begin{bmatrix} z\left(1 - \hat{L}\left(z^{-1}, \hat{b}'\right)\right) & \hat{M}\left(z^{-1}, \hat{b}'\right) \\ zS\left(z^{-1}, \hat{b}'\right) & zR\left(z^{-1}, \hat{b}'\right) \end{bmatrix}, \tag{22}$$

and

$$e(k+1) = x^T(k)\left[b(k) - b^T(k)\right] + n(k+1), \tag{23}$$

$n(k+1)$ is a white noise.

In the Matlab program the input u and the perturbation e of the leaded system are chosen as random type. For the $\hat{b}$ parameters of model $\hat{\text{A}}$ estimation one uses **ARX** operator from Matlab, which has the following syntax **th=ARX(z,nn),** where $\mathbf{z} = [y\ u] -$ matrix that contains the output vector (y) and the input vector (u); $\mathbf{nn} = [na\ nb\ nc] -$ defines the denominator order (na), numerator order (nb) and the model's delay (nc); **th** returns the estimated parameters in **theta** format (the elements of the vector $\hat{b}$) using the least square method [8]. The program plots the characteristics $y(t)$ and $\hat{y}(t)$, presented in fig.6; $y(t)$ is the output of the control system (A), while $\hat{y}(t)$ is the output of the estimated model $(\hat{\text{A}})$. As one can see in the above figure that the identification is made very well - the two signals overlap $(\hat{y} \to y)$.

V. IDENTIFICATION OF THE SYSTEM USING THE NEURAL NETWORKS' METHOD

Flying parameters' modification and atmospheric disturbances lead to difficulties in stability derivates calculus and to flying objects' models stabilization. That's why one may use identification methods or state estimate methods [8], [9], [10], [11], [12], [13], [14], [15]. The identification method presented in this paper is based on a neural network's use. As one can see in fig.7 for off-line identification, a feed-forward neural network is used; the network is trained by minimizing the quadratic quality indicator $J(k) = \frac{1}{2}e^2(k), e(k)$ being the training error [8], [13], [14], [15].

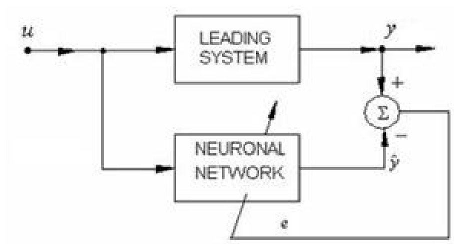

Fig.7 Dynamic model of the control system

The dynamics of the rockets' movement may be described by equation

$$y(k) = f\left(y(k-1)\, y(k-2) \cdots y(k-n_y)\ u(k-q) \cdots u(k-q-n_u+1)\right), \tag{24}$$

with $y = \overline{p}_R -$ the non-dimensional pressure inside the regulator, $u = F(s) -$ system's perturbation, $q -$ dead time; n_y and n_u express the system's order.

If nothing is known about the control system (n_y, n_u, q, f and n_h – the number of hidden layer neurons), by identification one determines these parameters. So that, starting from minimal neural network's architecture (numbers n_u, n_h, n_y and q) and imposing a value for the error $e(k)$ and a maxim number of training epochs, the neural networks begins the training process. If the error $e(k)$ doesn't tend to the desired

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value then n_u, n_y and n_h are modified [8], [13], [14], [15].

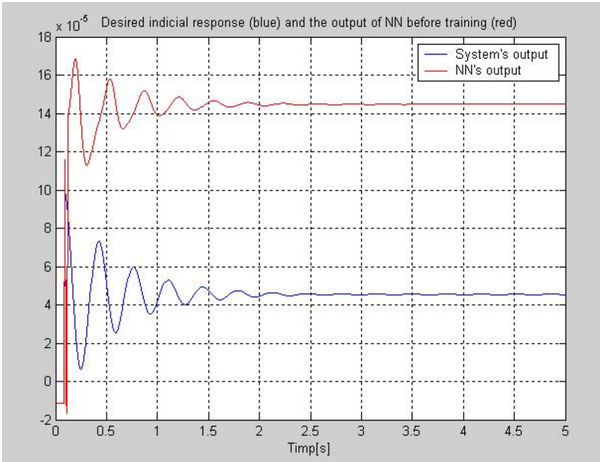

Fig.8 The output of the system from fig.2 (blue color) and the output of the NN (red color) before training.

For identification process's simulation of the rockets' dynamics with neural network one may use the discrete transfer function associated to the system. A neural network with one hidden layer is chosen. This network is characterized by $n_u = 1, n_y = 3, n_h = 5$ and $q = 0$.

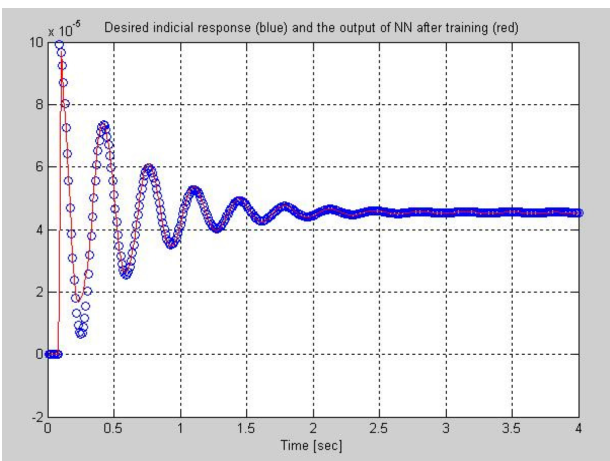

Fig.9 The output of the system from fig.2 (blue color) and the output of the NN (red color) after training.

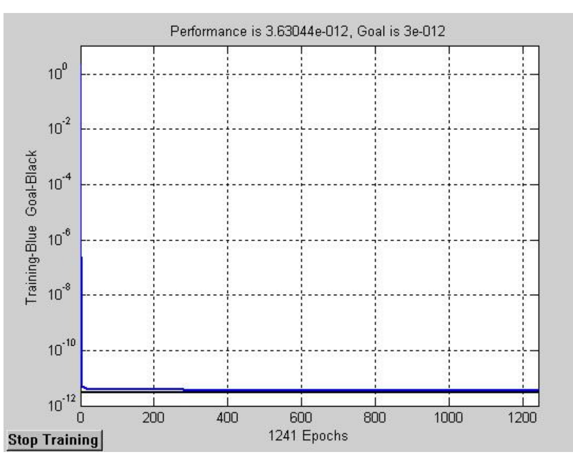

Fig.10 Dependence between the error of the training process and the training epochs' number for the system from fig.2

One chooses calculus steps (p), which is equal with vector y's components number (the values at respective moments of the control system). The matrix of neural network P is obtained (it has the dimension $((n_u + n_y) \times (p-3))$. Also, matrix T (of desired output of the network, which represents control system's output values matrix) is the matrix of the system output's values at time moments corresponding calculus steps; $\dim(T) = n_e \times (p-3), n_e$ being output neurons' number (in this example $n_e = 1$). In fig.8 one presents the output of the system from fig.2 (blue color) and the output of the NN (red color) before training. After the training process, the two signals overlap (fig.9).

Neural network's training is made using instruction "train" till the moment when $e(k) = y(k) - \hat{y}(k) \to e_{\text{imposed}}(k)$; $e_{\text{imposed}}(k) = 10^{-12}$ or until the number of training epochs is reached (in our example this number has been chosen 10000). In fig.10 the dependence between error $e(k)$ and training epochs' number is presented.

By neural network's training pseudo – neurons weights matrix W_1 and hidden layer neurons weights vector W_2 are obtained. Also, vectors B_1 and B_2, which contains polarization coefficients' values (bias) for neurons from hidden layer and for output neuron, respectively, are obtained. For this stabilization system they are

$$W_1 = 10^4 \begin{bmatrix} 3.5055 & 2.0411 & 0.8990 & -0.0008 \\ -1.9201 & -0.3109 & 2.0849 & 0.0031 \\ 0.5844 & -2.6337 & 2.3073 & 0.0023 \\ -0.1442 & 3.3056 & 2.4499 & -0.0009 \\ 2.5599 & -0.3618 & -2.1179 & 0.0025 \end{bmatrix}; B_1 = \begin{bmatrix} -8.0460 \\ -1.2923 \\ -2.0464 \\ -4.9513 \\ -1.5187 \end{bmatrix};$$

$$W_2 = [-0.015 \ -0.0003 \ 0.0003 \ 0.0004 \ 0.0001], B_2 = [-0.0146].$$

VI. CONCLUSIONS

The paper presents the mathematical model of a system, with direct action, for the regulation of the air debit in the aircrafts' cabins. It consists of a debit transducer, a regulator and an execution element.

One has determined the transfer functions (in closed loop - $H(s)$ and in open loop) of the system; a study of stability is made using Hurwitz conditions and the poles of the closed loop transfer function. All the poles of the systems are placed in the left complex semi-plane. This is a proof of system's stability. The system responds fast to a step input – the duration of the transient regimes is about 25 seconds. For these kind of systems (systems for the control of the cabin's pressure and air debit in the cabin), 25 seconds represent a good stabilization time.

Using two different methods (least square method and neural networks method), one makes the identification of the system. One obtains, using a Matlab program and a Simulink model, the indicial functions in the complex plane and in discrete plane, responses to impulse input in the complex and discrete planes, the poles, the zeros, the stability margins and so on. With the least square method (LSM) the output of the

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system and the output of the model for the two systems are plotted (fig.6). As one can see in this figure, the identification is made very well - the two signals overlap $(\hat{y} \rightarrow y)$.

The identification may also be made using neural networks. Using this method, one obtained the indicial response of the system and of the neural network before and after NN's training. Before training the two signals were different, but after training (1241 epochs) these signals overlap too. One also obtained the weights and the biases of the neural network. The dependence between the error of the training process and the training epochs number for the system is plotted (the error tends to its imposed value 10^{-12}).

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