UDC: 621.646:535.242.65(047.3)=20
COSATI: 13-11, 12-01, 14-02

Modeling of response times of pneumatic valve systems - model accordance with experimental research results

Dragan Knežević,PhD (Eng)[1]

The paper defines methods of mathematical modeling of response times of pneumatic blast-controllable valve systems as well as methods of evaluating the model $t_i = Ad^a V^b p^c L^e$ accordance with experimental research results. The analytical expressions of characteristic partial correlation coefficients and multiple correlation coefficients have been defined for qualitative model evaluation. A program has been realized for finding out a model of valve response time and for qualitative model evaluation. The application of described methods has been illustrated by defining response times of the blast-controlable valve of a mechana pneumatic system, controlability being dependent on working and geometric characteristics of valves, model accordance evaluation and experimental research results. The valves system response time models are defined. The level of agreement between the model obtained and experimental results is also estimated.

Key words: **pneumatic valve, response time, algorithm, mathematical modeling, model, correlation coefficient, model evaluation.**

Symbols:

t_i	-	valve system response times
d	-	pipeline diameter of the valve system
V	-	volume of the system compensation receptacle
p	-	working pressure in the pipeline of the valve system
L	-	system pipeline length
N	-	number of experimental units
$A^`, e_1, e_2, e_3, e_4$	-	equation system solutions
A, a, b, c, e	-	equation system solutions
A_1, a_1, b_1, c_1, e_1	-	equation system solutions
A_2, a_2, b_2, c_2, e_2	-	equation system solutions
$R_{i\cdot 1234}$	-	multiple correlation coefficient of the functional relationships in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$
$r_{i2\cdot 1}$	-	characteristic partial corelation coefficient of the functional relationship in the form $t_i = Ad_1^a V_2^b$
$r_{i3\cdot 12}$	-	charateristic partial corelation coefficient of the functional relationship in the form $t_i = Ad_1^a V_2^b p_3^c$
$r_{i3\cdot 124}, r_{i4\cdot 123}$ $r_{i2\cdot 134}, r_{i1\cdot 234}$	-	characteristic partial corelation coefficient of the functional relationship in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$
n_d	-	number of pipeline diameter levels in mechano-pneumatic systems
n_V	-	number of volume levels of the system compensation receptacle
n_p	-	number of working pressure levels of the pipeline system
n_L	-	number of pipeline length levels
t_2	-	valve system response time, (time from the moment of explosion detection to the moment of valve closing);
t_1	-	time from the moment of explosion detection to the shifting of a valve mobile make
$t_v = t_2 - t_1$	-	closing (response) time of valve systems

Purporse of research

THE goal of the research is to define methods of mathematical modeling of response times of blast-controllable pneumatic valve systems of as well as to give controllable of model accordance with experimental results.
The analytical expressions of characteristic partial correlation coefficients and multiple correlation coefficients for the qualitative model evaluation functional relationship in the form $t_i = Ad^a V^b p^c L^e$ have to be analytically defined.

Characteristic system values determining optimum (minimum) valve response times are being chosen on the basis of the obtained model of the valve (d, V, p, L) of the system $t_i = Ad_1^a V_2^b p_3^c L_4^e$ response time and numerical values of characteristic correlation coeficients.

For the functional relationship in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$ the coefficients of the best approximate plane regarding the least squares method of the respective, regressive plane, can be obtained by the regression analysis using the experimental data for t_i.

[1] Military Technical Institute (VTI), Katanićeva 15, 11000 Beograd

Based on the least squares method, regression analysis, analytical expressions of partial correlation coefficients and multiple correlation coefficient, algorithms and then a plan experiment, are defined for:

- modeling of valve system response times,
- numerical values of characteristic partial correlation coefficients, multiple correlation coefficients, applied in the qualitative model $t_i = Ad^a \mathrm{V}^{\mathrm{b}} p^c L^e$ evaluation with the experimental data for t_i.

The application of the given algorithms-methods is illustrated by an example.

Method for modeling valve response times

In general, the of valves response time of similar construction t_i is a function of four parameters and it can be expressed as follows [1-3]

$$t_i = Ad^a \mathrm{V}^{\mathrm{b}} p^c L^e \tag{1}$$

Models for the valve response time t_i depending on (d, V, p, L) can be obtained by the regression analysis, utilizing the least squares method as well as the experimental data for t_i. If the logarithms of eq. (1) are found

$$\ln t_i = \ln A + a \ln d + b \ln V + c \ln p + e \ln L \tag{2}$$

and substitutions are introduced

$$\begin{aligned} &Y_i = \ln t_i; a_0 = \ln A; a_1 = a; X_1 = \ln d; a_2 = b; \\ &X_2 = \ln V;\ \ a_3 = c;\ X_3 = \ln p;\ a_4 = e;\ X_4 = \ln L \end{aligned} \tag{3}$$

taking into consideration the test error ε, the linear regression equation is obtained

$$Y_i = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3 + a_4 X_4 + \varepsilon \tag{4}$$

The determination of constants $(a_0, a_1, a_2, a_3, a_4)$ could be done by processing the experimental data, utilizing the least squares method [3-11]. The method consists in minimizing the test results dispersion from the regression polynomials:

$$\left|\varepsilon\left(Y_i - a_0 - a_1 X_{1i} - a_2 X_{2i} - a_3 X_{3i} - a_4 X_{4i}\right)\right|_{\min} = \left(\varepsilon^2\right)_{\min} \tag{5}$$

The minimum dispersions can be obtained by deriving polynomial (5) with respect to the parameters needed and by reducing the derivatives to zero. After rearrangements, the linear regression equation system represented in the matrix form is obtained

$$\begin{bmatrix} N & \sum X_{1i} & \sum X_{2i} & \sum X_{3i} & \sum X_{4i} \\ \sum X_{1i} & \sum X_{1i}^2 & \sum X_{2i} X_{1i} & \sum X_{3i} X_{1i} & \sum X_{4i} X_{1i} \\ \sum X_{2i} & \sum X_{1i} X_{2i} & \sum X_{2i}^2 & \sum X_{3i} X_{2i} & \sum X_{4i} X_{2i} \\ \sum X_{3i} & \sum X_{1i} X_{3i} & \sum X_{2i} X_{3i} & \sum X_{3i}^2 & \sum X_{4i} X_{3i} \\ \sum X_{4i} & \sum X_{1i} X_{4i} & \sum X_{2i} X_{4i} & \sum X_{3i} X_{4i} & \sum X_{4i}^2 \end{bmatrix} \begin{bmatrix} a_o \\ a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = \begin{bmatrix} \sum Y_i \\ \sum X_{1i} Y_i \\ \sum X_{2i} Y_i \\ \sum X_{3i} Y_i \\ \sum X_{4i} Y_i \end{bmatrix} = \begin{bmatrix} B(0) \\ B(1) \\ B(2) \\ B(3) \\ B(4) \end{bmatrix} \tag{6}$$

When the experimental data, assorted as in Table 1, are processed and the equation system solved, the analytical expression for the valve response time is obtained in the form:

$$t_i = Ad_1^{e_1} V_2^{e_2} p_3^{e_3} L_4^{e_4} \tag{7}$$

The adequacy of the analytical expression (7) for the valve response time of mechano pneumatic systems has to be verified.

Method for verifying the adequacy of the valve response time model

The adequacy verification of the valve response time model is done on the basis of the numerical values of the multiple correlation coefficients $R_{i \cdot 123}$ of functional relationship (1), and characteristic partial correlation coefficients $r_{i1 \cdot 234}, r_{i2 \cdot 134}$, $r_{i3 \cdot 124}$ *and* $r_{i4 \cdot 123}$, of the functional relationship in the form (1), which have to be analytically defined.

After five - dimensional functional dependence of valve response time, it is necessary to define characteristic partial correlation coefficients and multiple correlation coefficient in the form $t_i = Ad^a \mathrm{V}^{\mathrm{b}} p^c L^e$.

Based on the analytical expressions of partial correlation coefficients and multiple correlation coefficients of the experimental results of the valve response time t_i, numerical values of characteristic partial correlation coefficients and multiple correlation coefficients are defined for the evaluation of the level of agreement between the valve response time model (7) and the experimental results.

Therefore, the following subscripts are introduced into expression (1): pipeline diameter d -1, volume V -2, presure p -3, and pipeline length L -4.

$$t_i = Ad_1^a V_2^b p_3^c L_4^e \tag{8}$$

Multiple correlation coefficient $R_{i \cdot 1234}$ ***for the relation*** $t_i = Ad_1^a V_2^b p_3^c L_4^e$

The multiple correlation coefficient $R_{i \cdot 1234}$ defines the level of agreement between the valves response time model (7) and the experimental results.

The multiple correlation coefficient $R_{i \cdot 1234}$ is defined by the following expression

$$R_{i \cdot 1234} = \sqrt{1 - \left[\left(1 - r_{i1}^2\right)\left(1 - r_{i2 \cdot 1}^2\right)\left(1 - r_{i3 \cdot 12}^2\right)\left(1 - r_{i4 \cdot 123}^2\right)\right]} \tag{9}$$

The partial correlation coefficients in expression (9) need to be analytically defined.

Partial correlation coefficient $r_{i2 \cdot 1}$

The partial correlation coefficient $r_{i2 \cdot 1}$ is defined by the following expression:

$$r_{i2 \cdot 1} = \frac{r_{i2} - r_{i1} r_{21}}{\sqrt{\left(1 - r_{i1}^2\right)\left(1 - r_{21}^2\right)}} \tag{10}$$

Partial correlation coefficient $r_{i3 \cdot 12}$

The partial correlation coefficient $r_{i3 \cdot 12}$ is defined by the following expression, from [4]

$$r_{i3\cdot 12} = \frac{r_{i3\cdot 2} - r_{i1\cdot 2} r_{31\cdot 2}}{\sqrt{\left(1-r_{i1\cdot 2}^2\right)\left(1-r_{31\cdot 2}^2\right)}} \tag{11}$$

The partial correlation coefficients $r_{i3\cdot 2}$, $r_{i1\cdot 2}$, and $r_{31\cdot 2}$, can be defined by the expressions

$$r_{i3\cdot 2} = \frac{r_{i3} - r_{i2} r_{32}}{\sqrt{\left(1-r_{i2}^2\right)\left(1-r_{32}^2\right)}} \tag{12}$$

$$r_{i1\cdot 2} = \frac{r_{i1} - r_{i2}\ r_{12}}{\sqrt{\left(1-r_{i2}^2\right)\left(1-r_{12}^2\right)}} \tag{13}$$

$$r_{31\cdot 2} = \frac{r_{31} - r_{32}\ r_{12}}{\sqrt{\left(1-r_{32}^2\right)\left(1-r_{12}^2\right)}} \tag{14}$$

Characteristic partial correlation coefficient $r_{i4\cdot 123}$ of the relationship in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$

The characteristic partial correlation coefficient $r_{i4\cdot 123}$ defines the level of agreement between the dependent variable t_i and the independent parameter L, when other independent parameters (d, V, p) are presumed to be constant. The partial correlation coefficient $r_{i4\cdot 123}$ of the functional relationship (8) also defines the probability of translating five-dimensional model (8) into the plane Lt_i model, when other independent parameters (d, V, p) are presumed to be constant. The partial correlation coefficient $r_{i4\cdot 123}$ is defined by the expression

$$r_{i4\cdot 123} = \frac{r_{i4\cdot 23} - r_{i1\cdot 23}\ r_{41\cdot 23}}{\sqrt{\left(1-r_{i1\cdot 23}^2\right)\left(1-r_{41\cdot 23}^2\right)}} \tag{15}$$

The partial correlation coefficients $r_{i4\cdot 23}$, $r_{i1\cdot 23}$ and $r_{41\cdot 23}$, existing in expression (25) can be defined by the expressions

$$r_{i4\cdot 23} = \frac{r_{i4\cdot 3} - r_{i2\cdot 3}\ r_{42\cdot 3}}{\sqrt{\left(1-r_{i2\cdot 3}^2\right)\left(1-r_{42\cdot 3}^2\right)}} \tag{16}$$

$$r_{i1\cdot 23} = \frac{r_{i1\cdot 3} - r_{i2\cdot 3}\ r_{12\cdot 3}}{\sqrt{\left(1-r_{i2\cdot 3}^2\right)\left(1-r_{12\cdot 3}^2\right)}} \tag{17}$$

$$r_{41\cdot 23} = \frac{r_{41\cdot 3} - r_{42\cdot 3}\ r_{12\cdot 3}}{\sqrt{\left(1-r_{42\cdot 3}^2\right)\left(1-r_{12\cdot 3}^2\right)}} \tag{18}$$

The partial correlation coefficients $r_{i4\cdot 3}$, $r_{i2\cdot 3}$ and $r_{42\cdot 3}$, existing in expressions (16), (17) and (18), can be defined by the expressions

$$r_{i4\cdot 3} = \frac{r_{i4} - r_{i3}\ r_{43}}{\sqrt{\left(1-r_{i3}^2\right)\left(1-r_{43}^2\right)}} \tag{19}$$

$$r_{i2\cdot 3} = \frac{r_{i2} - r_{i3}\ r_{23}}{\sqrt{\left(1-r_{i3}^2\right)\left(1-r_{23}^2\right)}} \tag{20}$$

$$r_{42\cdot 3} = \frac{r_{42} - r_{43}\ r_{23}}{\sqrt{\left(1-r_{43}^2\right)\left(1-r_{23}^2\right)}} \tag{21}$$

The partial correlation coefficients $r_{i1\cdot 3}$, $r_{12\cdot 3}$ and $r_{41\cdot 3}$, can be defined by the expressions

$$r_{i1\cdot 3} = \frac{r_{i1} - r_{i3}\ r_{13}}{\sqrt{\left(1-r_{i3}^2\right)\left(1-r_{13}^2\right)}} \tag{22}$$

$$r_{12\cdot 3} = \frac{r_{12} - r_{13}\ r_{23}}{\sqrt{\left(1-r_{13}^2\right)\left(1-r_{23}^2\right)}} \tag{23}$$

$$r_{41\cdot 3} = \frac{r_{41} - r_{43}\ r_{13}}{\sqrt{\left(1-r_{43}^2\right)\left(1-r_{13}^2\right)}} \tag{24}$$

Partial correlation coefficients r_{i1}, r_{i2}, r_{i3} and r_{i4}

The partial correlation coefficients r_{i1}, r_{i2}, r_{i3} *and* r_{i4} can be defined by the expressions:

$$r_{i1} = \frac{\sum Y_i X_{1i}}{\sqrt{\left(\sum X_{1i}^2\right)\left(\sum Y_i^2\right)}} = \frac{B(1)}{\sqrt{X(1,1)C(0)}} \tag{25}$$

$$r_{i2} = \frac{\sum Y_i X_{2i}}{\sqrt{\left(\sum X_{2i}^2\right)\left(\sum Y_i^2\right)}} = \frac{B(2)}{\sqrt{X(2,2)C(0)}} \tag{26}$$

$$r_{i3} = \frac{\sum Y_i X_{3i}}{\sqrt{\left(\sum X_{3i}^2\right)\left(\sum Y_i^2\right)}} = \frac{B(3)}{\sqrt{X(3,3)C(0)}} \tag{27}$$

$$r_{i4} = \frac{\sum Y_i X_{4i}}{\sqrt{\left(\sum X_{4i}^2\right)\left(\sum Y_i^2\right)}} = \frac{B(4)}{\sqrt{X(4,4)C(0)}} \tag{28}$$

Partial correlation coefficients r_{12}, r_{13} and r_{14}

The partial correlation coefficients r_{12}, r_{13} *and* r_{14} can be defined by the expressions

$$r_{12} \equiv r_{21} = \frac{\sum X_{1i} X_{2i}}{\sqrt{\left(\sum X_{1i}^2\right)\left(\sum X_{2i}^2\right)}} = \frac{X(1,2)}{\sqrt{X(1,1)X(2,2)}} \tag{29}$$

$$r_{13} \equiv r_{31} = \frac{\sum X_{1i} X_{3i}}{\sqrt{\left(\sum X_{1i}^2\right)\left(\sum X_{3i}^2\right)}} = \frac{X(1,3)}{\sqrt{X(1,1)X(3,3)}} \tag{30}$$

$$r_{14} \equiv r_{41} = \frac{\sum X_{4i} X_{1i}}{\sqrt{\left(\sum X_{4i}^2\right)\left(\sum X_{1i}^2\right)}} = \frac{X(4,1)}{\sqrt{X(4,4)X(1,1)}} \tag{31}$$

Partial correlation coefficients r_{23}, r_{24} and r_{34}

The partial correlation coefficients r_{23}, r_{24} *and* r_{34} defined by the analytical expressions

$$r_{23} \equiv r_{32} = \frac{\sum X_{2i} X_{3i}}{\sqrt{\left(\sum X_{2i}^2\right)\left(\sum X_{3i}^2\right)}} = \frac{X(2,3)}{\sqrt{X(2,2)X(3,3)}} \quad (32)$$

$$r_{24} \equiv r_{42} = \frac{\sum X_{4i} X_{2i}}{\sqrt{\left(\sum X_{4i}^2\right)\left(\sum X_{2i}^2\right)}} = \frac{X(4,2)}{\sqrt{X(4,4)X(2,2)}} \quad (33)$$

$$r_{34} \equiv r_{43} = \frac{\sum X_{4i} X_{3i}}{\sqrt{\left(\sum X_{4i}^2\right)\left(\sum X_{3i}^2\right)}} = \frac{X(4,3)}{\sqrt{X(4,4)X(3,3)}} \quad (34)$$

Algorithms of probabilities of translating models $t_i = Ad_1^a V_2^b p_3^c L_4^e$ into plane models

The influence of the qualitative analysis of the system (1) characteristic parameters (d, V, p, L) upon the valve response times is carried out on the basis of numerical values of the characteristic partial correlation coefficients $r_{i1\cdot 234}$, $r_{i2\cdot 134}$ $r_{i3\cdot 124}$ and $r_{i4\cdot 123}$, of the functional relationship $t_i = Ad_1^a V_2^b p_3^c L_4^e$. The coefficients $r_{i1\cdot 234}$, $r_{i2\cdot 134}$ and $r_{i3\cdot 124}$ have to be analytically defined.

Characteristic partial correlation coefficient $r_{i3\cdot 124}$ of the relationship in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$

The characteristic partial correlation coefficient $r_{i3\cdot 124}$ defines the level of agreement between the dependent variable t_i and the independent parameter p, when other independent parameters (d, V, L) are presumed to be constant. The partial correlation coefficient $r_{i3\cdot 124}$ of the functional relationship (8), alsa defines the probability of translating five-dimensional model (8) into the plane pt_i model, when other independent parameters (d, V, L) are presumed to be constant. The characteristic partial correlation coefficient $r_{i3\cdot 124}$ can be defined by the expression

$$r_{i3\cdot 124} = \frac{r_{i3\cdot 24} - r_{i1\cdot 24}\ r_{31\cdot 24}}{\sqrt{\left(1 - r_{i1\cdot 24}^2\right)\left(1 - r_{31\cdot 24}^2\right)}} \quad (35)$$

The partial correlation coefficients $r_{i3\cdot 24}$, $r_{i1\cdot 24}$ *and* $r_{31\cdot 24}$ can be defined by the expressions

$$r_{i3\cdot 24} = \frac{r_{i3\cdot 4} - r_{i2\cdot 4}\ r_{32\cdot 4}}{\sqrt{\left(1 - r_{i2\cdot 4}^2\right)\left(1 - r_{32\cdot 4}^2\right)}} \quad (36)$$

$$r_{i1\cdot 24} = \frac{r_{i1\cdot 4} - r_{i2\cdot 4}\ r_{12\cdot 4}}{\sqrt{\left(1 - r_{i2\cdot 4}^2\right)\left(1 - r_{12\cdot 4}^2\right)}} \quad (37)$$

$$r_{31\cdot 24} = \frac{r_{31\cdot 4} - r_{32\cdot 4}\ r_{12\cdot 4}}{\sqrt{\left(1 - r_{32\cdot 4}^2\right)\left(1 - r_{12\cdot 4}^2\right)}} \quad (38)$$

The partial correlation coefficients $r_{i3\cdot 4}$, $r_{i2\cdot 4}$ *and* $r_{32\cdot 4}$ can be defined by the expressions

$$r_{i3\cdot 4} = \frac{r_{i3} - r_{i4}\ r_{34}}{\sqrt{\left(1 - r_{i4}^2\right)\left(1 - r_{34}^2\right)}} \quad (39)$$

$$r_{i2\cdot 4} = \frac{r_{i2} - r_{i4}\ r_{24}}{\sqrt{\left(1 - r_{i4}^2\right)\left(1 - r_{24}^2\right)}} \quad (40)$$

$$r_{32\cdot 4} = \frac{r_{32} - r_{34}\ r_{24}}{\sqrt{\left(1 - r_{34}^2\right)\left(1 - r_{24}^2\right)}} \quad (41)$$

The partial correlation coefficients $r_{i1\cdot 4}$ *and* $r_{12\cdot 4}$ can be defined by the expressions

$$r_{i1\cdot 4} = \frac{r_{i1} - r_{i4}\ r_{14}}{\sqrt{\left(1 - r_{i4}^2\right)\left(1 - r_{14}^2\right)}} \quad (42)$$

$$r_{12\cdot 4} = \frac{r_{12} - r_{14}\ r_{24}}{\sqrt{\left(1 - r_{14}^2\right)\left(1 - r_{24}^2\right)}} \quad (43)$$

The partial correlation coefficient $r_{31\cdot 4}$ is defined by the expression

$$r_{31\cdot 4} = \frac{r_{31} - r_{34}\ r_{14}}{\sqrt{\left(1 - r_{34}^2\right)\left(1 - r_{14}^2\right)}} \quad (44)$$

Characteristic partial correlation coefficient $r_{i2\cdot 134}$ of the relationship in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$

The characteristic partial correlation coefficient $r_{i2\cdot 134}$ defines the level of agreement between the dependent variable t_i and the independent parameter V, when other independent parameters (d, p, L) are presumed to be constant. The partial correlation coefficient $r_{i2\cdot 134}$ of the functional relationship (8) also defines the probability of translating five-dimensional model (8) into the plane model, when other independent parameters (d, p, L) are presumed to be constant. The characteristic partial correlation coefficient $r_{i2\cdot 134}$ can be defined by the expression

$$r_{i2\cdot 134} = \frac{r_{i2\cdot 34} - r_{i1\cdot 34}\ r_{21\cdot 34}}{\sqrt{\left(1 - r_{i1\cdot 34}^2\right)\left(1 - r_{21\cdot 34}^2\right)}} \quad (45)$$

The partial correlation coefficients $r_{i2\cdot 34}$, $r_{i1\cdot 34}$ and $r_{21\cdot 34}$ can be defined by the expressions

$$r_{i2\cdot 34} = \frac{r_{i2\cdot 4} - r_{i3\cdot 4}\ r_{23\cdot 4}}{\sqrt{\left(1 - r_{i3\cdot 4}^2\right)\left(1 - r_{23\cdot 4}^2\right)}} \quad (46)$$

$$r_{i1\cdot 34} = \frac{r_{i1\cdot 4} - r_{i3\cdot 4}\ r_{13\cdot 4}}{\sqrt{\left(1 - r_{i3\cdot 4}^2\right)\left(1 - r_{13\cdot 4}^2\right)}} \quad (47)$$

$$r_{21\cdot 34} = \frac{r_{21\cdot 4} - r_{23\cdot 4}\ r_{13\cdot 4}}{\sqrt{\left(1 - r_{23\cdot 4}^2\right)\left(1 - r_{13\cdot 4}^2\right)}} \quad (48)$$

The partial correlation coefficients $r_{23\cdot 4}$, $r_{13\cdot 4}$ and $r_{21\cdot 4}$ can be defined by the expressions

$$r_{23\cdot4} = \frac{r_{23} - r_{54}\; r_{24}}{\sqrt{\left(1-r_{54}^2\right)\left(1-r_{24}^2\right)}} \tag{49}$$

$$r_{13\cdot4} = \frac{r_{13} - r_{14}\; r_{34}}{\sqrt{\left(1-r_{14}^2\right)\left(1-r_{34}^2\right)}} \tag{50}$$

$$r_{21\cdot4} = \frac{r_{21} - r_{24}\; r_{14}}{\sqrt{\left(1-r_{24}^2\right)\left(1-r_{14}^2\right)}} \tag{51}$$

Characteristic partial correlation coefficient $r_{i1\cdot234}$ of the relationship in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$

The characteristic partial correlation coefficient $r_{i1\cdot234}$ defines the level of agreement between the dependent variable t_i and the independent parameter d, when other independent parameters (V, p, L) are presumed to be constant. The partial correlation coefficient $r_{i1\cdot234}$ of the functional relationship (8) also defines the probability of translating five-dimensional model (8) into the plane dt_i model, when other independent parameters (V, p, L) are presumed to be constant. The characteristic partial correlation coefficient $r_{i1\cdot234}$ can be defined by the expression

$$r_{i1\cdot234} = \frac{r_{i1\cdot34} - r_{i2\cdot34}\; r_{12\cdot34}}{\sqrt{\left(1-r_{i2\cdot34}^2\right)\left(1-r_{12\cdot34}^2\right)}} \tag{52}$$

The partial correlation coefficient $r_{12\cdot34}$ is defined by the expression

$$r_{12\cdot34} = \frac{r_{12\cdot4} - r_{13\cdot4}\; r_{23\cdot4}}{\sqrt{\left(1-r_{13\cdot4}^2\right)\left(1-r_{23\cdot4}^2\right)}} \tag{53}$$

Presentation form of experimental results of the functional relationship in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$

The presentation form of experimental results of the functional relationship in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$, is given as Table 1.

Meaning of the symbols in Table 1:

- d – pipeline diameter of the valve system,
- V – volume of the system compensation receptacle,
- p – working pressure in the pipeline of the valve system,
- L – pipeline length of the valve system,
- t_2 – valve system response time, time from the moment of explosion detection to valve closing,
- t_1 – time from the moment of explosion detection to the moment of a shifting a valve mobile make,
- $t_v = t_2 - t_1$ – valve response (shuting) time.

The number of experimental units is:

$$N = n_d n_v n_p n_L \tag{54}$$

Where:

n_d – number of levels of system pipeline diameter

n_V – number of volume levels of the system compensation receptacle

n_p – number of working pressure levels in the pipeline system

n_L – number of pipeline length levels of the system.

Application of algorithms-methods

The application of the described methods has been presented by defining pneumatic response times of the $PPUV-400$ blast-controlable valve of a mechano pneumatic system, controlability being dependent on pipeline diameter d, volume V of the system compensation recep-

Table 1. Presentation form of experimental results of the functionals relationships in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$

d [mm]	V [l]	p [bar]	SYSTEM PIPELINE LENGHT L [mm]											
			L_1	L_2	...	L_{n_L}	L_1	L_2	...	L_{n_L}	L_1	L_2	...	L_{n_L}
			t_2 [ms]				t_1 [ms]				t_v [ms]			
d_{n_d}	V_1	p_1												
		...												
		p_{n_p}												
	·	p_1												
	·	...												
	·	p_{n_p}												
	V_{n_V}	p_1												
		...												
		p_{n_p}												

tacle, working pressure p and system pipeline length L, based on the experimental data for t_i.

Experimental investigation description

In order to define a model of valve response time, during preliminary research, tests were carried out concerning the effects of the overvalues of the mechanopneumatic systems with the $PPUV-400$ valves (optimum aerodynamic characteristics, closing time under direct effects of nuclear explosion air-blast waves, sensitivity thresholds of pneumatic closing) on the valve closing time during pneumatic closing.

The experiment consists of simultaneous registration of valve shuting times (t_2, t_1, t_v) of pneumatic closing, for: $n_d = 2$ - number of pipeline diameter levels, $n_V = 4$ - number of volume levels of the compensation receptacle, and $n_L = 4$ - number of pipeline length levels.

Here, we are dealing with a four-parameter experiment. The number of experimental units is:

$$N = n_d n_v n_p n_L = 160$$

Results of the experimental research

The results of the experimental research into response times of the valve system of $PPUV-400$ type, for inclusive compensation receptacles, (V≠0), are given in Table 2.

Table 2. Pneumatic response times (t_2, t_1, t_v) of five PPUV-400 valves forming a system for inclusive compensation receptacles ($V \neq 0$) - preliminary research

d [mm]	V [l]	p [bar]	SYSTEM PIPELINE LENGHT L [mm]											
			8350	12350	16350	24350	8350	12350	16350	24350	8350	12350	16350	24350
			t_2 [ms]				t_1 [ms]				t_v [ms]			
9	1.56	4	440	530	690	940	75	110	145	215	365	420	545	725
		6	270	365	455	630	65	95	125	184	205	270	330	446
		8	200	285	350	505	60	85	115	165	140	200	235	340
		10	170	230	300	435	54	80	104	152	116	150	196	283
		12	152	205	260	340	50	74	98	142	102	131	162	198
	2.08	4	390	525	690	930	75	110	145	214	315	415	545	716
		6	270	365	435	620	65	95	125	184	205	270	310	436
		8	200	285	345	480	58	85	112	165	142	200	233	315
		10	165	230	300	425	54	80	104	152	111	150	196	273
		12	150	200	255	340	50	74	96	142	100	126	159	198
	3.0	4	345	495	645	900	75	110	145	212	270	385	500	688
		6	250	350	420	615	65	95	125	189	185	255	295	433
		8	200	275	340	475	57	85	110	165	143	190	230	310
		10	161	225	295	415	53	80	105	152	108	145	180	263
		12	145	190	245	330	50	74	96	142	95	116	149	188
	4.02	4	345	490	640	875	74	110	145	212	271	380	495	663
		6	245	345	420	610	65	95	125	182	180	250	295	428
		8	200	275	335	470	57	85	112	165	143	190	223	305
		10	160	225	285	405	53	80	104	152	107	145	181	253
		12	145	190	240	325	50	74	96	142	95	116	144	183
14	1.56	4	230	320	490	625	58	85	113	165	172	235	377	460
		6	140	215	265	365	50	75	96	140	90	140	169	225
		8	105	165	195	285	45	67	88	128	60	98	107	157
		10	95	125	160	240	40	60	80	118	55	65	80	122
		12	85	115	140	195	38	57	75	110	47	58	65	85
	2.08	4	210	295	420	605	58	86	112	165	152	209	308	440
		6	130	210	260	355	50	75	97	140	80	135	163	215
		8	105	160	190	275	45	66	87	125	60	94	103	150
		10	90	125	160	230	41	61	80	115	49	64	80	115
		12	80	112	140	195	38	57	75	110	42	55	65	85
	3.0	4	210	290	370	510	58	85	112	164	152	205	258	346
		6	130	200	260	350	50	75	96	140	80	125	164	210
		8	105	155	190	270	45	65	87	125	60	90	103	145
		10	95	130	160	225	40	61	80	115	55	69	80	110
		12	80	110	140	195	36	56	75	110	44	54	65	85
	4.02	4	200	280	365	505	57	86	112	164	143	194	253	341
		6	130	200	255	346	50	75	95	140	80	125	160	206
		8	105	150	180	265	45	65	86	125	60	85	94	140
		10	90	128	154	220	40	61	80	115	50	67	74	105
		12	80	110	136	190	36	56	75	110	44	54	61	80

Models of pneumatic valve response times for inclusive compensation receptacles

In general, valve response times t_i are functions concerning four parameters of the form:

$$t_2 = Ad_1^a V_2^b p_3^c L_4^e \tag{55}$$

$$t_1 = A_1 d_1^{a_1} V_2^{b_1} p_3^{c_1} L_4^{e_1} \tag{56}$$

$$t_v = A_2 d_1^{a_2} V_2^{b_2} p_3^{c_2} L_4^{e_2} \tag{57}$$

For the functional relationship in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$ on the basis of experimental results of response times (t_2, t_1, t_v) of the $PPUV-400$ valve and for inclusive compensation receptacles ($V \neq 0$), givenin Table 2, a valve response time model is defined, as well as numerical values of characteristic partial correlation coefficients and multiple correlation coefficients for qualitative model evaluation.

Analytical expression of the closing time t_2 of the PPUV-400 valve system for $V \neq 0$ has the following form

$$t_2 \Big|_{V \neq 0} = 31.0301\, d^{-1.2949}\ \mathrm{V}^{-0.0771}\ \mathrm{p}^{-0.9009}\ L^{0.7522} \tag{58}$$

which correlates the experimental data for t_2 given in Table 2. with a probability of **99.996**% (respectively **91.38**% of the plane pt_2 for d=const; V=const; L=const, and **98.71**% of the plane Lt_2 for d=const; V=const; p=const). The partial corelation coefficients and multiple correlation coefficients are as follows:

r_{13}=0.9777;	r_{34}=0.9807;	$r_{i2\cdot4}$=0.0784;	$r_{41\cdot3}$=0.8748;
r_{12}=0.9273;	r_{i4}=0.9648;	$r_{i3\cdot4}$=-0.7750;	$r_{12\cdot3}$=0.3927;
r_{14}=0.9947;	r_{i2}=0.9245;	$r_{31\cdot24}$=0.1051;	$r_{i1\cdot3}$=0.7736;
r_{i1}=0.9860;	$r_{31\cdot4}$=0.1064;	$r_{i1\cdot24}$=-0.6242;	$r_{i2\cdot3}$=0.3985;
r_{23}=0.9143;	$r_{12\cdot4}$=0.0536;	$r_{i3\cdot24}$=-0.7755;	$r_{i4\cdot3}$=0.9798;
r_{24}=0.9301;	$r_{i1\cdot4}$=0.6256;	**$r_{i3\cdot124}$=0.9138**	$r_{41\cdot23}$=0.8504;
r_{i3}=0.9965;	**$r_{i4\cdot23}$=09762;**	$r_{i3\cdot2}$=0.7745;	**$r_{i4\cdot123}$=0.9871;**
$r_{i3\cdot12}$=0.0530;	$r_{31\cdot2}$=0.8571;	$r_{i2\cdot1}$=0.1636; i	$r_{i1\cdot2}$=0.9022;
$r_{32\cdot4}$=0.0276;	$r_{i1\cdot23}$=0.7317;	$r_{42\cdot3}$=0.4233;	**$R_{i\cdot1234}$=0.9996.**

Analytical expression of the time t_1 - time from the moment of explosion detection to the moment shutting the of $PPUV-400$ valve system mobile make, for $V \neq 0$ has the following form

$$t_1 \Big|_{V \neq 0} = 0.2184\, d^{-0.5962}\ \mathrm{V}^{-0.0097}\ p^{-0.3729}\ L^{0.8686} \tag{59}$$

that probability **99.99**% (respectively **93.23**% of the plane pt_1, at d=const; V=const; L=const, and **99.55**% of the plane Lt_1, at d=const; V=const; p=const) accordance with of experimental data for t_1, of the table **2** is given, at where of the partial corelation coefficients and multiple correlation coefficient

r_{i1}=0.9886;	$r_{i1\cdot4}$=0.7492;	$r_{i3\cdot24}$=-0.6934;	$r_{i4\cdot3}$=0.9843;
r_{i2}=0.9266;	$r_{i2\cdot4}$=-0.0915;	**$r_{i3\cdot124}$=-0.9323;**	$r_{i1\cdot23}$=0.7397;
r_{i3}=0.9712;	$r_{i3\cdot4}$=0.6928;	$r_{i1\cdot3}$=0.7807;	$r_{i4\cdot23}$=0.9815;
r_{i4}=0.9983;	$r_{i1\cdot24}$=-0.7485;	$r_{i2\cdot3}$=0.4006;	**$r_{i4\cdot123}$=0.9955;**
$r_{i1\cdot2}$=0.9192;	$r_{i3\cdot2}$=0.8146;	$r_{i3\cdot12}$=0.1316;	$r_{i2\cdot1}$=0.1752;
			$R_{i\cdot1234}$=0.9999.

Analytical expression of the PPUV-400 valve system closing time t_v, for $V \neq 0$ has the following form

$$t_v \Big|_{V=0} = 195.0169\, d^{-1.7106}\ \mathrm{V}^{-0.1103}\ p^{-1.1884}\ L^{0.6792} \tag{60}$$

that probability **99.90**% (respectively **88.38**% of the plane pt_v at d=const; V=const; L=const, and **97.37**% of the plane Lt_v at d=const; V=const; p=const) accordance with of experimental data for t_v, of the table **2** is given, at where of the partial corelation coefficients and multiple correlation coefficient:

r_{i1}=0.9804;	$r_{i1\cdot4}$=-0.6003;	$r_{i3\cdot24}$=-0.7651;	$r_{i4\cdot3}$=0.9653;
r_{i2}=0.9202;	$r_{i2\cdot4}$=-0.0772;	**$r_{i3\cdot124}$=-0.8838;**	$r_{i1\cdot23}$=0.6950;
r_{i3}=0.9561;	$r_{i3\cdot4}$=-0.7647;	$r_{i1\cdot3}$=0.7414;	$r_{i4\cdot23}$=0.9593;
r_{i4}=0.9929;	$r_{i1\cdot24}$=-0.6018;	$r_{i2\cdot3}$=0.3880;	**$r_{i4\cdot123}$=0.9737;**
$r_{i1\cdot2}$=0.8676;	$r_{i3\cdot2}$=0.7242;	$r_{i3\cdot12}$=0.0759;	$r_{i2\cdot1}$=0.1501;
			$R_{i\cdot1234}$=0.9990.

The model adequacy verification

The model adequacy verification is done utilizing numerical values of the multiple correlation coefficients $R_{i\cdot123}$ and the characteristic partial corelation coefficients $r_{i3\cdot124}$ and $r_{i4\cdot123}$.

Program for finding out the model of valve system response time

Based on the given algorithms, a program has been realized for finding out the model of blast-controllable valve system response time, applied in the qualitative model evaluation with the experimental data for t_i.

Conclusion

The methods for modeling response times of pneumatic blast-controllable valve systems during pneumatic closing have been defined as well as the evaluation of the model accordance $t_i = Ad_1^a V_2^b p_3^c L_4^e$ with the experimental results of the research.

The analytical expressions of characteristic partial correlation coefficients $r_{i1\cdot234}$, $r_{i2\cdot134}$, $r_{i3\cdot124}$ and $r_{i4\cdot123}$, and multiple correlation coefficients $R_{i\cdot12345}$ have been defined for the qualitative model evaluation.

Through characteristics partial correlation coefficients $r_{i1\cdot234}$, $r_{i2\cdot134}$, $r_{i3\cdot124}$ and $r_{i4\cdot123}$, for the functional relationship $t_i = Ad_1^a V_2^b p_3^c L_4^e$, the probability of influence of the system characteristic parameters (d, V, p, L) on valve response times is defined in an original manner, for a case when other characteristic parameters of the system, are constant.

Based on the algorithms, a program has been realized for finding out the model of valve system response time, applied in the qualitative model evaluation with the experimental data for t_i.

The application of the described methods has been illustrated by defining pneumatic response times of the $PPUV-400$ blast-controllable valve of a mechano pneumatic system, controlability being dependent on a pipeline diameter, volume of the system compensation receptacle, working pressure and system pipeline length.

Author's contribution is in original definitions of: method of valve response time modeling, design experiment, model adequacy estimation, analytical expressions of characteristic partial correlation coefficients $r_{i1\cdot234}$, $r_{i2\cdot134}$, $r_{i3\cdot124}$ $r_{i4\cdot123}$ and multiple correlation coefficient of the functional relationship in the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$.

A special contribution author's is in an original definition of probabilities of translating of five dimensional models of the form $t_i = Ad_1^a V_2^b p_3^c L_4^e$ into plane models.

In the multicriteria analysis, characteristic system values determining optimum (minimum) valve response time are being chosen on the basis of the obtained model of the valve (d, V, p, L) system $t_i = Ad_1^a V_2^b p_3^c L_4^e$ response time and the numerical values of characteristic correlation coeficients.

The algorithms presented here are useful in some other technical areas (hydraulics, pneumatics, aerodynamics, automatic control, etc.) for defining and solving problems which can not be exactly described utiziling the laws of physics. The given problem has been treated as a hyperplane problem.

References

[1] KNEŽEVIĆ,D. *Modeliranje hidrauličkih karakteristika ventila sa ravnim sedištem vretena* **(***Modeling of hydraulic characteristics of valves with flat spindle seat).* XXXII Kongres o klimatizaciji, grejanju, hlađenju, sa međunarodnim učešćem, KGH 2001., Beograd, 5.-7. decembra 2001. godine, Centar Sava, SMEITS, Beograd, 2001., pp. 249-258.

[2] ŠIKOPARIJA,V. *Teorija sličnih modela.* Fakultet tehničkih nauka Univerziteta u Novom Sadu, Novi Sad, 1980.

[3] KNEŽEVIĆ,D. *Pneumatički ventili-hiperravanski problem modeliranje i ocena modela (Pneumatic valve-hyper plane problem and model evaluation).* Međunarodni naučno-stručni skup, Istraživanje i razvoj mašinskih elemenata i sistema, Jahorina-IRMES`2002. Zbornik radova, Mašinski fakultet, Srpsko Sarajevo, 2002., pp 875 –880.

[4] NENADOVIĆ,M**.** *Metode optimizacije sistema* SANU, Beograd, 1980.

[5] NENADOVIĆ,M. *Matematička obrada podataka dobijenih merenjem.* SANU, posebno izdanje, knjiga DLXXII, Odeljenje tehničkih nauka, Beograd, 1988.

[6] VUKADINOVIĆ,S. Elementi teorije verovatnoće i matematičke statistike, drugo izmenjeno izdanje. *Privredni pregled*, Beograd, 1978.

[7] ANĐONOVIĆ,J. *Osnovi računa verovatnoće i teorije najmanjih kvadrata.* Naučna knjiga, Beograd,1986.

[8] FERGUSON,S. Mathematical statistics, New York, 1967.

[9] FREUND,J. E. Mathematical statistics, New York, 1971.

[10] PANTELIĆ,I. *Uvod u teoriju inženjerskog eksperimenta*. Radnički univerzitet "Radivoj Čirpanov", Novi Sad, 1986.

[11] DUDUKOVIĆ,B., MILOSAVLJEVIĆ,Đ. *Planiranje eksperimenta i optimizacija procesa.* IHTM Centar za tehnoekonomiku i programiranje, Beograd, 1976.

Received: 26.5.2003

Definisanje vremena odziva pneumatičkih ventila sistema, ocena saglasnosti modela i rezultata eksperimenta

Definisane su metode matematičkog modeliranja vremena odziva ventila sistema upravljivih efektima eksplozije, ocene nivoa saglasnosti dobijenih modela $t_i = Ad^a V^b p^c L^e$ i eksperimentalnih rezultata istraživanja. Za kvalitativnu ocenu dobijenih modela definisani su analitički izrazi karakterističnih koeficijenata parcijalne korelacije i koeficijent višestruke korelacije. Izrađen je program za pronalaženje modela vremena odziva ventila sistema i kvalitativnu ocenu modela. Primena metoda prikazana je na primeru definisanja vremena odziva ventila sistema, upravljivog efektima eksplozije, pri pneumatičkom zatvaranju, u zavisnosti od radnih i dimenzionalnih karakteristika sistema, i ocene modela. Ilustracija primene izloženih metoda prikazana je na primeru definisanja vremena odziva ventila sistema, upravljivog efektima eksplozije, pri pneumatičkom zatvaranju, u zavisnosti od radnih i dimenzionalnih karakteristika sistema, i ocene modela. Definisani su modeli vremena odziva ventila sistema. Izvršena je ocena nivoa saglasnosti dobijenih modela i rezultata eksperimentalnih istraživanja.

Ključne reči: **pneumatički ventil, vreme odziva, algoritam, matematičko modeliranje, model, koeficijent korelacije, ocena modela.**

Définition du temps de réponse d'un système de soupapes pneumatiques, l'évaluation de l'accord du modèle avec les résultats d'essais

Le papier définit les méthodes de modélisation mathématique du temps de réponse d'un système de soupapes commandées par explosion chez les systèmes mécanopneumatiques. L'accord du modèle $t_i = Ad^a V^b p^c L^e$ avec les résultats d'essais est défini aussi bien que les expressions analytiques des coefficients caractéristiques de la correlation partielle et le coefficient de la correlation multiple afin d'effectuer une éstimation qualitative des modèles obtenus. Un programme est conçu pour trouver le temps de réponse des soupapes et pour l'évaluation qualitative des modèles. L'application des algorithmes donnés est illustrée en définissant le temps de réponse t_i d'une soupape commandée par explosion d'un système mécanopneumatique pendant la fermeture pneumatique par rapport aux dimensions, caractéristiques opérationnelles du système et l'évaluation du modèle. Le modèle obtenu et les valeurs numériques des coefficients de la correlation servent comme la base pour le choix des valeurs caractéristiques du système (*d,V,p,L*) qui déterminent les temps minimaux (optimaux) de réponse des soupapes.

Mots-clés: **soupape pneumatique, temps de réponse, algorithme, modélisation mathématique, modèle, coefficient de la correlation, évalution du modèle.**