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[1.] Přemysl MATOUŠEK

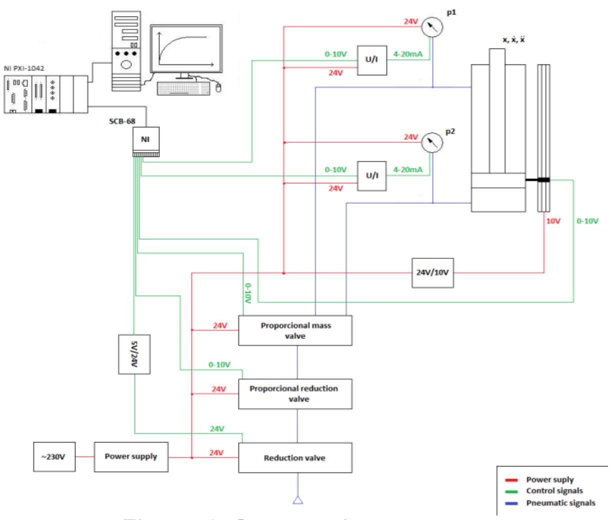
ADAPTIVE CONTROL OF PNEUMATIC SERVOMECHANISM

[1.] TECHNICAL UNIVERSITY OF LIBEREC, FACULTY OF MECHANICAL ENGINEERING,
DEPARTMENT OF APPLIED CYBERNETICS, LIBEREC, CZECH REPUBLIC

ABSTRACT: The pneumatic positional servomechanism is highly non - linear system and that is why its identification and control is more exacting than at hydraulic or electric servomechanisms. To be able to reach a better control process it is not enough only to identify the system and than set the parameters of the controller but the system also has to be identified continuously and simultaneously with the identification of the parameters of the controller which have to be re - set depending on the achieved mathematical model. This article briefly describes the two main parts that constitute an adaptive control. The first part describes a design of an optimal structure of mathematical model that allows the continuous identification. The second part describes a design of an adaptive space-state controller whereby the adaptive control is implemented.
KEYWORDS: pneumatic system; identification; model; state – space

INTRODUCTION

The pneumatic servomechanism is a non - linear and integral system. The air is a gas characterized by its compressibility, concurrently the passive resistances arise during the motion of the piston, and these resistances cause the non - linearity. This is why it is not effective to take several measurements, identify the system and set the parameters of the controller on the basis of the resultant mathematical model, because at each motion of the piston we get different parameters of the mathematical model. And the controller adjusted to a concrete mathematical model would not control exactly. Thus the system has to be identified continuously to get the most accurate mathematical model that is corresponding to the given state of the system. At the same time it is necessary to re - set the parameters of the controller, depending on the achieved mathematical model. The pneumatic system and the wiring of the components is shown in figure 1.



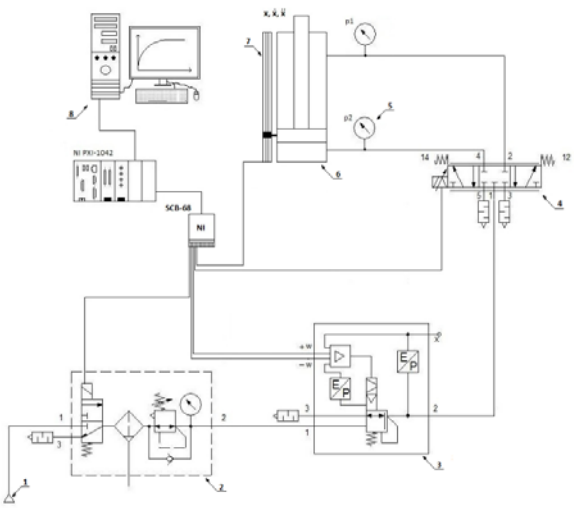


Figure 1: Pneumatic system

Figure 2: Simplified circuit

(1 – compressor, 2 – pressure regulator, 3 – proportional pressure regulator, 4 – proportional directional valve, 5 – pressure sensors, 6 - cylinder with one - sided piston rod, 7 - linear displacement encoder, 6 – control system)

❖ PNEUMATIC SYSTEM

Pneumatic positional servomechanism consists of the cylinder with one - side piston rod with maximal stroke 960mm, proportional directional valve MPYE–5–1/8–HF–010-B, proportional pressure regulator VPPM-6L–L-1-618-0L10H-A4P-S1C1 and pressure regulator HEE-D-MINI-24 with the filter LF-D-5M-MINI. The position of the piston rod is measured by means the linear displacement encoder with the 1000mm measurement length.

The feeding is realized by the power supply 24V/2A. This voltage serves for feeding the pressure regulator, proportional pressure regulator and proportional directional valve and it is also regulated to 10V voltage, by which the linear displacement encoder is supplied. This displacement encoder is connected with the piston of the pneumatic drive. The voltage on the slider appropriate to the position of the piston is applied to connector block SCB - 68 of the data acquisition card, its analog inputs and outputs are from the range of 0 - 10V.

The air from the compressor is brought to the input of the pressure regulator, through which the air supply to the whole system is switched on or off. The pressure regulator is switched on by the 24V and to be able to switch it on by the digital output of the data acquisition card (5V), the signal convert from 5V to 24V has to be ensured. This convert is ensured by the switching transistor.

Constant pressure in the system is ensured by means of proportional pressure regulator. This regulator is controlled by the 0 - 10V voltage, where 1V equals to 1bar. As the analog output of the data acquisition card is in the range of 0 - 10V, the proportional pressure regulator is controlled straight by the means of output voltage of the card. This is how the air regulation to the required constant pressure is ensured.

When the air pressure is set to the required value, the air is brought to the input of the proportional directional valve. The motion of the slide valve is also controlled by the 0 - 10V voltage because the proportional directional valve is connected in the same way as the proportional pressure regulator. The system further contains of two DMP 331 pressure sensors that measure the running pressure over and below the piston and they also generate the flow signal in the range of 4 – 20mA. To be able to connect the sensors to the data acquisition card two I/U converters are used. They bring the current signal to 0 – 10V voltage. The data acquisition card is a part of the control system PXI - 1042Q and an external connector block SCB - 68 is attached to it. PXI system communicates with the PC by means of Ethernet interface and LabView software is used to the control of the system. Simplified electrical scheme is shown in the figure 2.

❖ IDENTIFICATION OF PNEUMATIC SYSTEM

To be able to realize the online identification of the pneumatic positional servomechanism, it is necessary to determine the order of the numerator and denominator of the system transfer. The system transfer was set by jumps in voltage excitation of various voltages, when the response of the system was recorded into the folder and was later identified in Matlab programme according to the quadratic criterion:

$$J_2 = \int [y(t) - y_m(t)]^2 = \sum_0^N (y(t) - y_m(t))^2 \tag{1}$$

where $y(t)$ is the output of the system, $y_m(t)$ is the response of the model of the system.

The identification was realized with different structures of the model, when the most accurate transfer was achieved with the structures of the model in form:

$$G_1(s) = \frac{b_0}{a_2 s^2 + a_1 s}, G_2(s) = \frac{b_1 s + b_0}{a_3 s^3 + a_2 s^2 + a_1 s}, G_3(s) = \frac{b_1 s + b_0}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s} \tag{2, 3, 4}$$

where a_4 – a_1 are the coefficients of the numerator of the system transfer, b_2 – b_0 are the coefficients of the denominator of the system transfer.

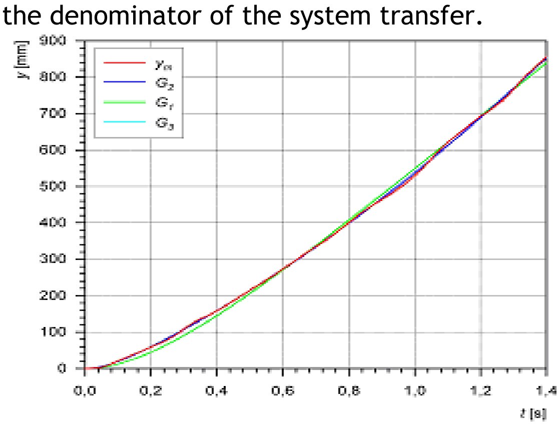


Figure 3: Response of the pneumatic system at 3, 4 and 5 bar pressures

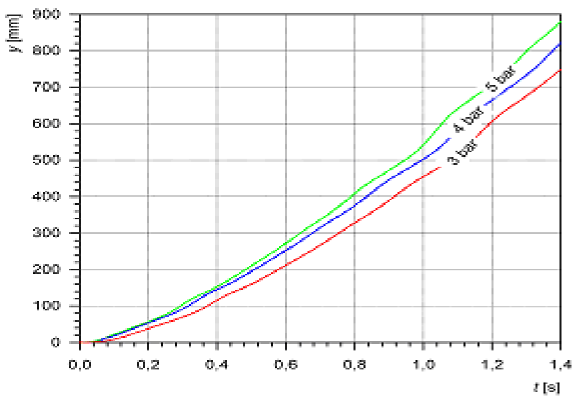


Figure 4: Comparison of the models $G_1(s)$, $G_2(s)$, $G_3(s)$

In figure 3 there is the response of the pneumatic system for pressures of 3, 4 and 5 bars with the step change U = 4,6V voltage on the proportional directional valve and then in the figure 4 there is the progress of the system response $y_m(t)$ and the comparison of the mathematical models $G_1(s)$, $G_2(s)$ *and* $G_3(s)$ for pressure of 4 bar at this jump.

In the figure 4 there is noticeable that the differences among the models $G_1(s)$, $G_2(s)$, $G_3(s)$of the pneumatic system are minimal, but on the more detailed investigation it is clear that the transfer $G_2(s)$ reaches the most accurate reset and this is why it was finally chosen for the online identification of the system. It is needful to convert this transfer from the continuous to the discreet area to be able to realize the project of model structure, the convert from continuous to the discreet area was implemented by the Matlab software.

The model for online identification was chosen from three kinds, model ARX, ARMAX and Box - Jenkins. Model Box - Jenkins cannot be used for this identification, because its error differs from an order over against ARX and ARMAX models. The structure of ARX and ARMAX models results from the structure of discreet transfer that was achieved by the convert of the continuous model to the discreet model. Structure ARX model is used in [3 3 1] form, structure of ARMAX model in [3 1 3 1] form, where the difference equations are set by equation 5 and 6. The difference between the error of the ARX and ARMAX models during the identification of the system is nearly insignificant and it is shown in the figure 6. Finally, the ARX model was chosen for the online identification.

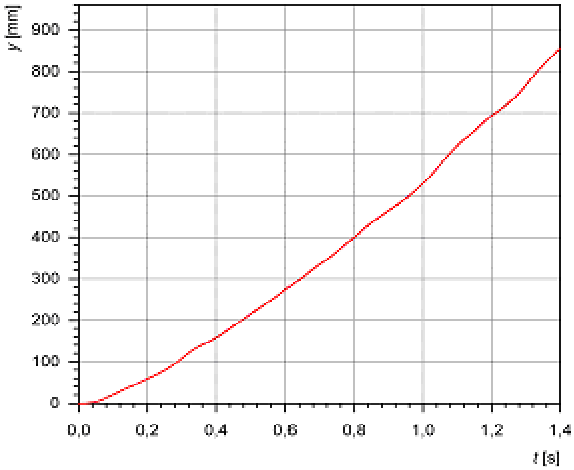


Figure 5: Identification of the system by ARX model

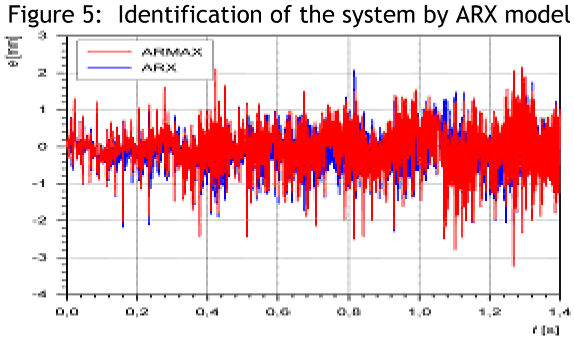


Figure 6: Difference of ARX and ARMAX models

The signal from the linear displacement encoder is filtered, because it is extensively noisy. Kalman filter with the polynomials degree of 3 and number of samples 8 is used for the filtration. The comparison of the progress of the output signal ARX model with the structure that is defined by equation 6 and a measured signal $y_m(t)$ is shown in the figure 5.

$$(1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}) y(k) = (b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3}) u(k) + e(k) \qquad (4)$$

$$(1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}) y(k) = (b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3}) u(k) + (1 + c_1 z^{-1}) e(k) \qquad (5)$$

where $a_3 - a_1$, $b_3 - b_1$, c_1 are coefficients of the difference equations of ARX and ARMAX models, $u(k)$ is exciting signal, $y(k)$ the output of the model and $e(k)$ the error of the model.

In the figure 5 it is obvious, that the response of the pneumatic system $y_m(t)$ is nearly identical with the output of the ARX model and the error arised during the identification reaches at most 3,7 mm and so it can be neglected during the next calculations.

STATE DESCRIPTIONS

The pneumatic system is regulated by the adaptive LQ controller, hence the discreet transfer of the ARX model has to be converted to state - space form (7). This conversion resides is based on the compilation of the state matrixes, when the observable canonical form was chosen for the state description. This canonical form reconstructs the response of the pneumatic system $y_m(k)$. The state vector consists of three state variables $x_1(k)$, $x_2(k)$, $x_3(k)$.

$$G(s) = \frac{b_1 s + b_0}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s} \quad \rightarrow \quad \begin{aligned} x(k+1) &= Mx(k) + Nu(k) \\ y(k) &= Cx(k) + Du(k) \end{aligned} \qquad (6,7)$$

where $x(k)$ is the state vector [n, l], $u(k)$ is the input vector [p, l], $y(k)$ is the output vector , M is the state matrix [n,n], N is the input matrix [n, p], C is the output matrix [l, n], D is the feed forward matrix [l, l].

REDUCED ORDER OBSERVER

The state vector consists of three variables where the first one is the measured response of the pneumatic system $y_m(k)$. The response of this system (position of the piston rod of the pneumatic cylinder) is measured by the linear displacement encoder and so it is not necessary to observe the variable $x_1(k)$ of the state vector. The two rest variables $x_2(k)$, $x_3(k)$ of the state vector are observed (8, 9). Not a full – state observer but the reduced order observer (designed by *D.G. Luenberger*) is used for the observation of the state vector.

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \\ x_3(k+1) \end{bmatrix} = \begin{bmatrix} y_m(k+1) \\ x_{E1}(k+1) \\ x_{E2}(k+1) \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \begin{bmatrix} y_m(k) \\ x_{E1}(k) \\ x_{E2}(k) \end{bmatrix} + \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix} u(k) \tag{8}$$

$$y(k) = \begin{bmatrix} C_1 & C_2 & C_3 \end{bmatrix} \begin{bmatrix} y_m(k) \\ x_{E1}(k) \\ x_{E2}(k) \end{bmatrix} + Du(k) \tag{9}$$

During the project of the observer it is necessary to select the eigenvalues so that the error of the observe converges to zero. The dynamic qualities of the error of the observe are given by the eigenvalues $\lambda_{1,2}$, that's why the eigenvalues of the designed observer are zero. The observer was designed on the basis of equations 10, 11, 12, 13, 14 where $x_E(k)$ is the estimate $\hat{x}_E(k)$.

$$\overline{\hat{x}_E}(k+1) = M_E \overline{\hat{x}_E}(k) + H_E y_m(k) + N_E u(k) \tag{10}$$

$$\hat{x}_E(k) = \overline{\hat{x}_E}(k) + Q y_m(k) \tag{11}$$

$$M_E = F - QG \tag{12}$$

$$H_E = H - QM_{11} - Q * G * Q + FG \tag{13}$$

$$N_E = K - QN_{11} \tag{14}$$

where $H = \begin{bmatrix} M_{21} \\ M_{31} \end{bmatrix}, K = \begin{bmatrix} N_{21} \\ N_{31} \end{bmatrix}, F = \begin{bmatrix} M_{22} & M_{23} \\ M_{32} & M_{33} \end{bmatrix}, G = \begin{bmatrix} M_{12} & M_{13} \end{bmatrix}$.

The process of the state vector of the designed observer at jump in voltage U = 4,6V on the proportional directional valve is shown in the figure 7.

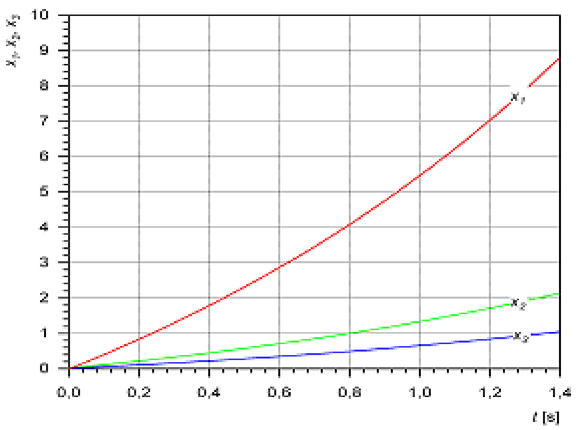


Figure 7: Simulation of the process of the state vector

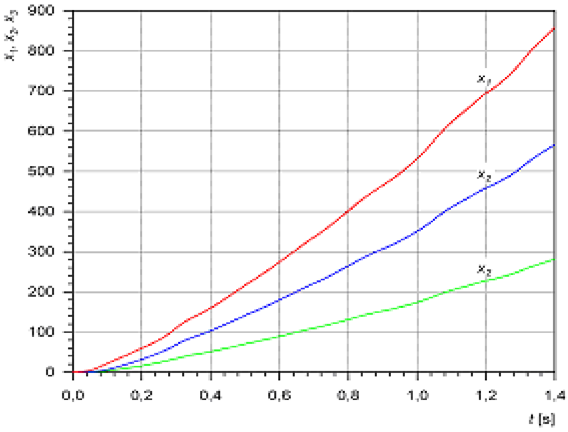


Figure 8: Real process of the state vector

In the figure 8 we can see the real process of the state vector of the designed observer. The calculation of the observer comes from the online identification of the pneumatic system by the ARX model. In each period of sampling we obtain new coefficients of the convert of the system. These coefficients are used for the construction of the new state matrixes that are necessary for the calculation of the state vector.

LQ CONTROLLER

The regulation of the piston position of the pneumatic system in the state space is implemented by means of LQ controller that is quadratically optimal for the linear systems. The controller minimizes the quadratic criterion for the discrete systems in the equation:

$$J(u(k)) = \sum_{k=1}^{N} (X^T(k)Qx(k) + u^T(k)Ru(k)) + x^T(N)Px(N) \tag{15}$$

where *Q* is a positive - definite Hermitian or real symmetric matrix, *R* is a positive - definite or real symmetric matrix.

For the calculation of LQ controller that regulates the position of the piston we used simplified quadratic criterion in this equation:

$$J(u(k)) = \sum_{k=1}^{N} (X^T(k)Qx(k) + u^T(k)Ru(k)) \tag{16}$$

where *Q* is a positive - semidefinite Hermitian or real symmetric matrix, *R* is a positive - semidefinite or real symmetric matrix.

The calculation of LQ controller comes from Riccati equation, when the condition of matrixes convergence *V = V(k) = V(k + 1)* is kept:

$$V = Q + M^T VM - M^T VN(R + N^T SN)^{-1} N^T VM \tag{17}$$

and the resultant increase of the feedback of the state LQ controller is defined by this relation:

$$K = [R + N^T VN]^{-1} N^T VM \tag{18}$$

Our LQ controller should also equalize the influence of the constant failure and should follow the jump in voltage of the control quantity, so it is necessary to place a digital adder into the circuit. This adder increases the order of the system and the equation 8, 9 changes to form:

$$\begin{bmatrix} x(k+1) \\ x_4(k+1) \end{bmatrix} = \begin{bmatrix} M & 0 \\ CM & E \end{bmatrix} \begin{bmatrix} x(k) \\ x_4(k) \end{bmatrix} + \begin{bmatrix} N \\ CN \end{bmatrix} u(k) \quad (19)$$

$$y(k) = \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x(k) \\ x_4(k) \end{bmatrix} \quad (20)$$

where *x(k)* is the state vector of variables $x_1(k)$, $x_2(k)$, $x_3(k)$ *and* $x_4(k)$ is the state variable that arised, because the adder was added to the system.

In the figures 9 and 10 there we can see the simulation of the regulation of the pneumatic system with the reduced order observer and LQ controller with the 0,2 m/s jump change of speed.

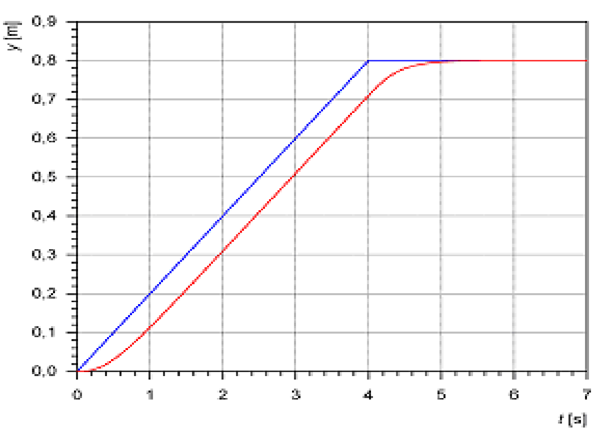


Figure 9: Simulated process of position

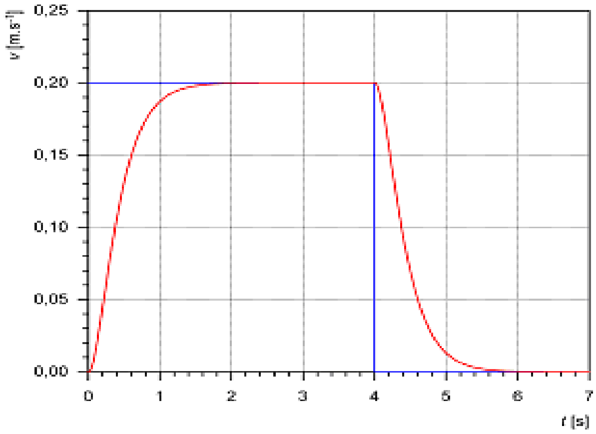


Figure 10: Simulated process of speed

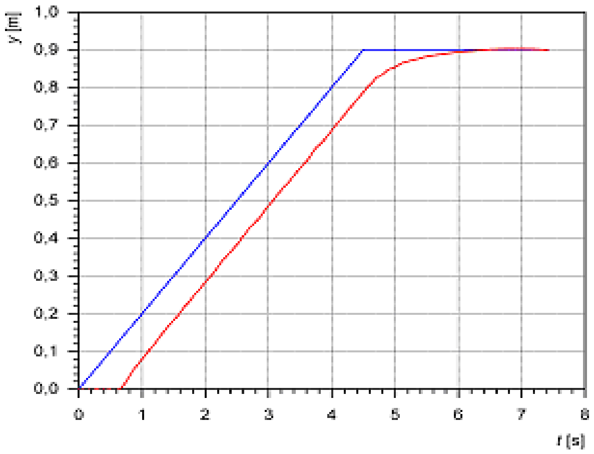


Figure 11: Real process of position

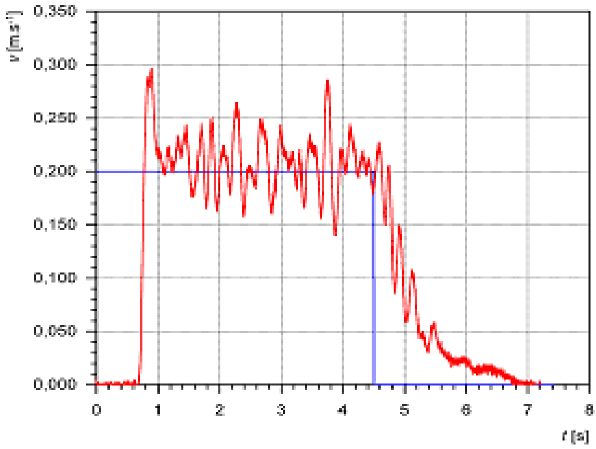


Figure 12: Real process of speed

In the figures 11 and 12 we can see the process of the regulation by means of LQ controller on the real pneumatic system to the speed step 0,2 m/s. During the regulation of the piston position at first the system is identified by ARX model. Then the state description of the system is made. As soon as the state matrixes are made the actual value of the state vector is calculated. The parameters of LQ controller are re - calculated after the completion of the calculation of the state vector. The output of LQ controller (action interference) is observed on the directional valve

❖ CONCLUSION

The differences between the simulation and the real process of the regulation are evident from the figures 9 and 11. The differences between the smooth process of the simulation and the real process are caused mainly by the compressibility of the air and the passive resistances that have to be overcame during the motion of the piston. The passive resistances are also caused by the linear displacement encoder at which the stronger passive resistances arise in some places of the stroke. These resistances are probably caused by twisting the rod that connects the slider of the sensor with the end of the pneumatic piston inside the sensor case.

During the regulation by means of the state controller it is necessary to set the matrixes of weight coefficients accurately. If these matrixes are not set accurately the piston of pneumatic cylinder passes the required position at a high speed and after then it started to move to the required position at a low speed. When the matrix is set incorrectly the second most often behaviour of the piston occurs. It moves slowly to the required position from the beginning of setting the position. Another problem that we face at the pneumatic servomechanism is keeping the stable position. If we let the pneumatic servomechanism in a rest for a while, the air leakage occurs due to the untightness.

This leakage deflects the piston from the equilibrium position so that the controller vibrates the piston around the required position.

The position at this pneumatic servomechanism is controlled only by means of the positional feedback and the LQ controller. At the hydraulic servomechanisms not only the positional feedback with the P controller is used for the control, but also the internal speed feedback with PI controller. We would like to eliminate an uneven speed of the piston motion of the pneumatic cylinder with the help of installation of the speed feedback as we can see it at hydraulic servomechanisms. Regulation of the position and the speed should not be implemented by the cascade connection of P and PI controllers but by two state LQ controllers that would be connected in cascade.

❖ REFERENCES

[1] Strejc, V.: Stavová teorie lineárního diskrétního řízení. Academia, Praha 1978
[2] Modrlák, O.: Úvod do diskrétní parametrické identifikace. Skripta Liberec, 2004
[3] Modrlák, O.: Základy analýzy a syntézy ve stavovém prostoru. Skripta Liberec, 2004
[4] Balátě, J.: Automatické řízení. BEN-Technická literatura, Praha 2003

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