$$\hat{y}(k+j)=\frac{B}{A}u(k+j)+\frac{D}{A}v(k+j)+E_j e_s(k+j)+\frac{F_j}{\Delta A}e_s(k) \quad (27)$$

From original equation (22) we can compute the disturbance and substitute to equation (25)

$$\begin{aligned}\hat{y}(k+j)&=\frac{B}{C}\left[\frac{C}{\Delta A}-z^{-j}\frac{F_j}{\Delta A}\right]\Delta u(k+j)+\\&+\frac{D}{C}\left[\frac{C}{\Delta A}-z^{-j}\frac{F_j}{\Delta A}\right]\Delta v(k+j)+\frac{F_j}{C}y(k)+E_j e_s(k+j)\end{aligned} \quad (28)$$

After substitution we obtain

$$\begin{aligned}\hat{y}(k+j)&=\frac{BE_j}{C}\Delta u(k+j)+\frac{DE_j}{C}\Delta v(k+j)+\\&+\frac{F_j}{C}y(k)+E_j e_s(k+j)\end{aligned} \quad (29)$$

Now let us make two simplifications: a white noise case will be considered and future noise values will be further omitted.

$$\hat{y}(k+j)=BE_j\Delta u(k+j)+DE_j\Delta v(k+j)+F_j y(k) \quad (30)$$

We can define polynomials Gj ans Lj as follows

$$G_j=BE_j \qquad L_j=DE_j \quad (31)$$

$$\hat{y}(k+j)=G_j\Delta u(k+j)+L_j\Delta v(k+j)+F_j y(k) \quad (32)$$

For the design of the j – step ahead predictor the following Diophantine equation is solved

$$1=E_j\Delta A+z^{-j}F_j \quad (33)$$

Further is necessary to solve a recursion of Diophantine equation (33). Particular polynomials in the Diophantine equation can be expanded as follows

$$\tilde{A}(z^{-1})=\Delta A(z^{-1})=1+(1-a_1)z^{-1}+(a_1-a_2)z^{-2}+a_2z^{-3} \quad (34)$$

$$E_j(z^{-1})=E_{j,0}+E_{j,1}z^{-1}+E_{j,2}z^{-2}+\cdots+E_{j,j-1}z^{j-1} \quad (35)$$

$$F_j(z^{-1})=F_{j,0}+F_{j,1}z^{-1}+F_{j,2}z^{-2}+\cdots+F_{j,j-1}z^{j-1} \quad (36)$$

Let us consider the Diophantine equation corresponding to the prediction $\hat{y}(k+j+1)$

$$1=E_{j+1}(z^{-1})\tilde{A}(z^{-1})+z^{-(j+1)}F_{j+1}(z^{-1}) \quad (37)$$

It is possible to subtract Diophantine equation (33) from Diophantine equation (37) and obtain the following expression

$$\begin{aligned}0&=\left(E_{j+1}(z^{-1})-E_j(z^{-1})\right)\tilde{A}(z^{-1})+\\&+z^{-j}\left(z^{-1}F_{j+1}(z^{-1})-F_j(z^{-1})\right)\end{aligned} \quad (38)$$

Now it is possible to define the following term

$$E_{j+1}(z^{-1})-E_j(z^{-1})=\tilde{R}(z^{-1})+R_j z^{-1} \quad (39)$$

After substitution

$$\begin{aligned}0&=\tilde{R}(z^{-1})\tilde{A}(z^{-1})+\\&+z^{-j}\left(R_j\tilde{A}(z^{-1})+z^{-1}F_{j+1}(z^{-1})-F_j(z^{-1})\right)\end{aligned} \quad (40)$$

it is obvious that $\tilde{R}(z^{-1})=0$ in order to obtain the zero polynomial on the left side of equation (40). The polynomial E can be then computed recursively according to the following expression

$$E_{j+1}(z^{-1})=E_j(z^{-1})+R_j z^{-j} \quad (41)$$

Following expressions can be obtained from equation (40)

$$\begin{aligned}&R_j=F_{j,0}\\&F_{j+1,i}=F_{j,i+1}-R_j\tilde{A}_{i+1} \quad \text{for} \quad i=0\cdots\delta(F_{j+1})\end{aligned} \quad (42)$$

Initial conditions for the recursion are as follows

$$E_1=1 \qquad F_1=z(1-\tilde{A}) \quad (43)$$

By making the polynomials

$$E_j(z^{-1})B(z^{-1})=G_j(z^{-1})+z^{-j}G_{jp}(z^{-1}) \quad (44)$$

$$E_j(z^{-1})D(z^{-1})=L_j(z^{-1})+z^{-j}L_{jp}(z^{-1}) \quad (45)$$

the prediction equation can be written as

$$\begin{aligned}\hat{y}(k+j)&=G_j(z^{-1})\Delta u(k+j)+L_j(z^{-1})\Delta v(k+j)+\\&+G_{jp}(z^{-1})\Delta u(k-1)+L_{jp}(z^{-1})\Delta v(k-1)+F_j(z^{-1})y(k)\end{aligned} \quad (46)$$

The last three terms of equation (46) depend on past values of the process output, input and disturbance and represent the free response of the process. The first two terms depend on future values of control increments and disturbances and represent the forced response of the system. Equation (46) can be rewritten as

$$\hat{y}(k+j)=G_j(z^{-1})\Delta u(k+j)+L_j(z^{-1})\Delta v(k+j)+y_{0j} \quad (47)$$

Where

$$y_{0j}=G_{jp}(z^{-1})\Delta u(k-1)+L_{jp}(z^{-1})\Delta v(k-1)+F_j(z^{-1})y(k) \quad (48)$$

is the free response.

In case of the second order system, the polynomial $\tilde{A}$ has the following form

$$\tilde{A}(z^{-1})=\Delta A(z^{-1})=1+(a_1-1)z^{-1}+(a_2-a_1)z^{-2}-a_2z^{-3} \quad (49)$$

Initial conditions of the recursion are

$$\boldsymbol{E}_1=1 \quad (50)$$

$$\begin{aligned}F_1&=z(1-\tilde{A})=1-a_1+z^{-1}(a_1-a_2)+z^{-2}a_2=\\&=f_0+z^{-1}f_1+z^{-2}f_2\end{aligned} \quad (51)$$

Initialization of the matrix of the free response and the matrices of the dynamics is following

$$\boldsymbol{x} = \begin{bmatrix} f_0 & f_1 & f_2 & b_2 & d_2 \end{bmatrix} \tag{52}$$

$$\boldsymbol{G} = b_1 \qquad \boldsymbol{L} = d_1 \tag{53}$$

The recursion then proceeds according to previously introduced steps.

$$R = f_0 \tag{54}$$

$$f_0 = f_1 - R(a_1 - 1) \tag{55}$$

$$f_1 = f_2 - R(a_2 - a_1) \tag{56}$$

$$f_2 = Ra_2 \tag{57}$$

$$\boldsymbol{E} = [\boldsymbol{E} \quad R] \tag{58}$$

Extension of the matrices of the dynamics and the free response is as follows:

$$\boldsymbol{G} = \begin{bmatrix} \boldsymbol{G} \\ b_1\boldsymbol{E}(i+1) + b_2\boldsymbol{E}(i) \end{bmatrix} \tag{59}$$

$$\boldsymbol{L} = \begin{bmatrix} \boldsymbol{G} \\ d_1\boldsymbol{E}(i+1) + d_2\boldsymbol{E}(i) \end{bmatrix} \tag{60}$$

$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{x} \\ f_0 \quad f_1 \quad f_2 \quad b_2\boldsymbol{E}(i+1) \; d_2\boldsymbol{E}(i+1) \end{bmatrix} \tag{61}$$

4.2 Method Based on Direct Computation from CARIMA Model

This method is based on an analytical derivation of certain predictions and subsequent recursive derivation of later predictions. The number of predictions which are necessary to be computed directly depends on the order of the system. The a priori analytical computation, which is required, enables to reduce computational complexity of the previously introduced method. This is important in the adaptive predictive control where the computation must be performed in each sampling period.

The difference equation of the CARIMA model without the unknown term can be expressed as:

$$\begin{aligned} y(k) &= (1-a_1)y(k-1) + (a_1-a_2)y(k-2) + a_2y(k-3) + \\ &+ b_1\Delta u(k-1) + b_2\Delta u(k-2) + d_1\Delta v(k-1) + d_2\Delta v(k-2) \end{aligned} \tag{62}$$

It was necessary to directly compute three step ahead predictions in a straightforward way by establishing of previous predictions to later predictions. The model order defines that computation of one step ahead prediction is based on the three past values of the system output. The prediction equation (24) after modification can be written in a matrix form

$$\begin{aligned} \overbrace{\begin{bmatrix} \hat{y}(k+1) \\ \hat{y}(k+2) \\ \hat{y}(k+3) \end{bmatrix}}^{\hat{\boldsymbol{y}}} &= \overbrace{\begin{bmatrix} g_1 & 0 \\ g_2 & g_1 \\ g_3 & g_2 \end{bmatrix} \begin{bmatrix} \Delta u(k) \\ \Delta u(k+1) \end{bmatrix}}^{\boldsymbol{G}\Delta\boldsymbol{u}} + \\ &+ \overbrace{\begin{bmatrix} l_1 & 0 \\ l_2 & l_1 \\ l_3 & l_2 \end{bmatrix} \begin{bmatrix} \Delta v(k) \\ \Delta v(k+1) \end{bmatrix}}^{\boldsymbol{L}\Delta\boldsymbol{v}} + \\ &+ \overbrace{\begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} \\ p_{21} & p_{22} & p_{23} & p_{24} & p_{25} \\ p_{31} & p_{32} & p_{33} & p_{34} & p_{35} \end{bmatrix} \begin{bmatrix} y(k) \\ y(k-1) \\ y(k-2) \\ \Delta u(k-1) \\ \Delta v(k-1) \end{bmatrix}}^{\boldsymbol{y}_0} \end{aligned} \tag{63}$$

It is possible to divide computation of the predictions to recursion of the free response and recursion of the matrices of the dynamics.

All the elements $p(i,j)$ i=1…3, j=1…5 have to be directly computed to initialize the recursion.

$$\begin{aligned} & p_{11} = (1-a_1) \quad p_{12} = (a_1 - a_2) \quad p_{13} = a_2 \quad p_{14} = b_2 \quad p_{15} = d_2 \\ & p_{21} = (1-a_1)^2 + (a_1 - a_2) \quad p_{22} = (1-a_1)(a_1-a_2) + a_2 \\ & p_{23} = a_2(1-a_1) \quad p_{24} = (1-a_1)b_2 \quad p_{25} = (1-a_1)d_2 \\ & p_{31} = (1-a_1)^3 + 2(1-a_1)(a_1-a_2) + a_2 \\ & p_{32} = (1-a_1)^2(a_1-a_2) + a_2(1-a_1) + (a_1-a_2)^2 \\ & p_{33} = a_2(1-a_1)^2 + (a_1-a_2)a_2 \\ & p_{34} = (1-a_1)^2 b_2 + (a_1-a_2)b_2 \\ & p_{35} = (1-a_1)^2 d_2 + (a_1-a_2)d_2 \end{aligned} \tag{64}$$

The next row of the free response matrix is repeatedly computed on the basis of the three previous predictions until the prediction horizon is achieved.

$$\begin{aligned} p_{41} &= (1-a_1)p_{31} + (a_1-a_2)p_{21} + a_2p_{11} \\ p_{42} &= (1-a_1)p_{32} + (a_1-a_2)p_{22} + a_2p_{12} \\ p_{43} &= (1-a_1)p_{33} + (a_1-a_2)p_{23} + a_2p_{13} \\ p_{44} &= (1-a_1)p_{34} + (a_1-a_2)p_{24} + a_2p_{14} \\ p_{45} &= (1-a_1)p_{35} + (a_1-a_2)p_{25} + a_2p_{15} \end{aligned} \tag{65}$$

The forced response in equation (63) has following form:

$$\boldsymbol{G}\Delta\boldsymbol{u} = \begin{bmatrix} b_1 & 0 \\ b_1(1-a_1)+b_2 & b_1 \\ (a_1-a_2)b_1+(1-a_1)^2 b_1+(1-a_1)b_2 & (1-a_1)b_1+b_2 \end{bmatrix} \begin{bmatrix} \Delta u(k) \\ \Delta u(k+1) \end{bmatrix} \quad (66)$$

$$\boldsymbol{L}\Delta\boldsymbol{v} = \begin{bmatrix} d_1 & 0 \\ d_1(1-a_1)+d_2 & d_1 \\ (a_1-a_2)b_1+(1-a_1)^2 d_1+(1-a_1)d_2 & (1-a_1)d_1+d_2 \end{bmatrix} \begin{bmatrix} \Delta v(k) \\ \Delta v(k+1) \end{bmatrix} \quad (67)$$

The recursion of the matrices $\boldsymbol{G}$ and $\boldsymbol{L}$ is similar to the recursion of the free response matrix. The next element of the first column is repeatedly computed and the remaining columns are shifted. This procedure is performed repeatedly until the prediction horizon is achieved. If the control horizon is lower than the prediction horizon a number of columns in the matrix $\boldsymbol{G}$ is reduced. Computation of new elements is performed as follows:

$$\begin{aligned} g_4 &= (1-a_1)g_3 + (a_1-a_2)g_2 + a_2 g_1 \\ l_4 &= (1-a_1)l_3 + (a_1-a_2)l_2 + a_2 l_1 \end{aligned} \quad (68)$$

5 Disturbance Rejection by Polynomial Methods

Degrees of the particular polynomials in the control loop are obtained from equations (18).

$$\begin{aligned} &\deg Q = \deg A + \deg f_v - 1 = 2+2-1 = 3 \\ &\deg \tilde{P} = \deg A - 1 = 2-1 = 1 \\ &\deg R = \deg f_w - 1 = 1-1 = 0 \\ &\deg T = 2\deg A + \deg f_v - \deg f_w - 1 = 4+2-1-1 = 4 \\ &\deg D = 2\deg A + \deg f_v - 1 = 4+2-1 = 5 \end{aligned} \quad (69)$$

Consequently, the particular polynomials are in the following form

$$\begin{aligned} &Q(z^{-1}) = q_0 + q_1 z^{-1} + q_2 z^{-2} + q_3 z^{-3} \\ &\tilde{P}(z^{-1}) = 1 + p_1 z^{-1} \\ &R(z^{-1}) = r_0 \\ &T(z^{-1}) = t_0 + t_1 z^{-1} + t_2 z^{-2} + t_3 z^{-3} + t_4 z^{-4} \\ &D(z^{-1}) = m_0 + m_1 z^{-1} + m_2 z^{-2} + m_3 z^{-3} + m_4 z^{-4} + m_5 z^{-5} \end{aligned} \quad (70)$$

After substitution of polynomials (70) to Diophantine equation (16) we can obtain a system of linear equations with unknown controllers parameters

$$\begin{bmatrix} b_1 & 0 & 0 & 0 & 1 \\ b_2 & b_1 & 0 & 0 & a_1-\alpha \\ 0 & b_2 & b_1 & 0 & 1-\alpha a_1+a_2 \\ 0 & 0 & b_2 & b_1 & a_1-\alpha a_2 \\ 0 & 0 & 0 & b_2 & a_2 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \\ p_1 \end{bmatrix} = \begin{bmatrix} m_1+\alpha-a_1 \\ m_2-a_2-1+\alpha a_1 \\ m_3-a_1+\alpha a_2 \\ m_4-a_2 \\ m_5 \end{bmatrix} \quad (71)$$

Similar approach can be used for Diophantine equation (17) to obtain the parameter r_0

$$r_0 = \frac{1+m_1+m_2+m_3+m_4+m_5}{b_1+b_2} \quad (72)$$

The control law which ensues from Fig. 2 and transfer functions (10) is then given as

$$\begin{aligned} u(k) &= r_0 w(k) - q_0 y(k) - q_1 y(k-1) - q_2 y(k-2) - q_3 y(k-3) - \\ &-(p_1-\alpha)u(k-1) - (1-\alpha p_1)u(k-2) - p_1 u(k-3) \end{aligned} \quad (73)$$

6 Simulation Examples

Both controllers were tested by simulation control of a range of systems. Control of the following system is given as an example

$$G_p(z) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{0{,}20z^{-1}+0{,}17z^{-2}}{1-1{,}51z^{-1}+0{,}55z^{-2}} \quad (74)$$

$$G_v(z) = \frac{D(z^{-1})}{A(z^{-1})} = \frac{0{,}10z^{-1}-0{,}20z^{-2}}{1-1{,}51z^{-1}+0{,}55z^{-2}} \quad (75)$$

A sinusoid of angular frequency 1 rad/sec and amplitude 1 was applied as the disturbance. Tuning parameters of the predictive controller are the weighting factor λ and the prediction and control horizons. The controller based on polynomial methods has as tuning parameters poles of the polynomial *D*.

The performances of both controllers were compared by means of control quality criteria, which are the sum of powers of control errors and the sum of increments of manipulated variables.

For both controllers it is possible to set the rate of changes in the manipulated variable (for the predictive controller by the parameter λ and for the controller based on polynomial methods by poles of the polynomial *D*). As larger changes in manipulated variable as better quality of asymptotic tracking of reference signal is achieved. However, large changes of manipulated variable are often undesirable. In order to compare the performances of both controllers, the rate of changes of the manipulated variable was set to be approximately the same in both cases. For the polynomial controller a suitable multiple pole 0,2 was found. The predictive controller was tuned by the weighting factor to achieve approximately the same sum of increments of the manipulated variable. It was achieved for $\lambda = 0{,}077$.

In Fig. 3, Fig. 4, Fig. 7 and Fig. 8 are time responses of control without the disturbance. In Fig. 9 and Fig. 10 are time responses of control with the predictive controller with the disturbance when the prediction equations do not include information about the disturbance. The controller based on polynomial methods was designed for the specific shape of the disturbance and thus it is not possible to simulate control without the disturbance rejection. In Fig. 5, Fig. 6, Fig. 11, Fig. 12, Fig. 13 and Fig. 14 are time responses with the disturbance when both controllers take into account the disturbance. It is obvious that the influence of disturbance was suppressed.

In case of predictive controller, the objective function (1) was used for computation of control sequence. We considered an unconstrained case even though possibility of incorporation of constraints is very important in predictive control since one of the main advantages of predictive control is its ability to deal effectively with constraints. But the paper is focused on another part of predictive control: computation of predictions with incorporation of known disturbance. So that the simulated control problem was simplified to be unconstrained. In this case computation of optimal control is a direct problem of linear algebra.

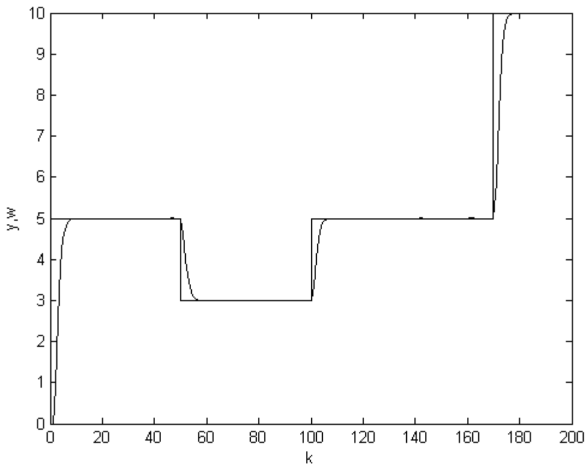

Fig. 3 Controller based on polynomial methods-control without disturbance

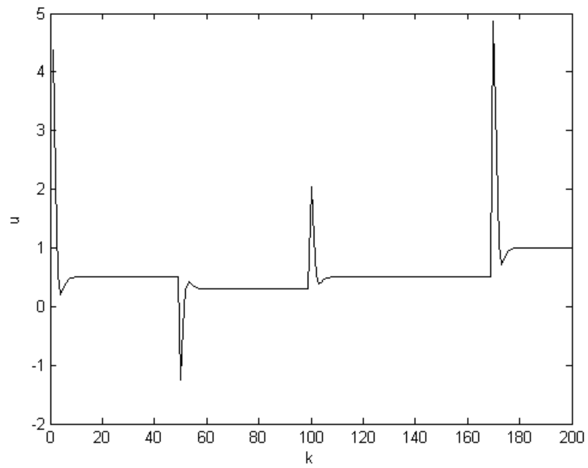

Fig. 4 Controller based on polynomial methods-control without disturbance-manipulated variable

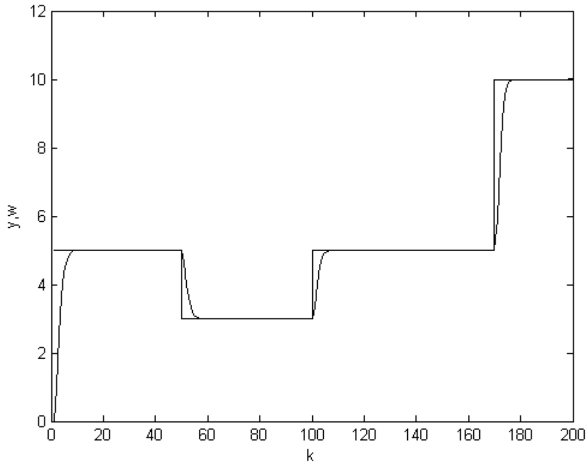

Fig. 5 Controller based on polynomial methods-control with disturbance with disturbance rejection

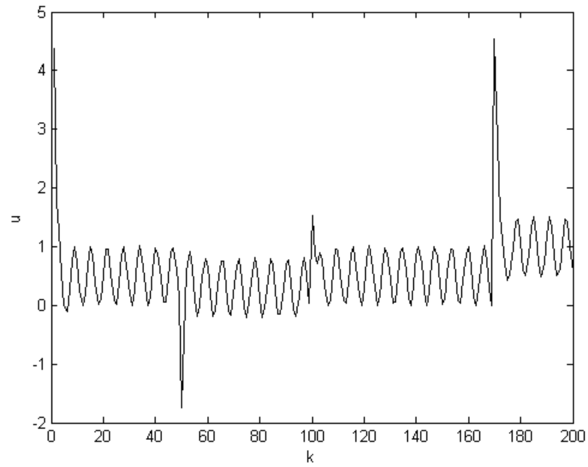

Fig. 6 Controller based on polynomial methods-control with disturbance with disturbance rejection-manipulated variable

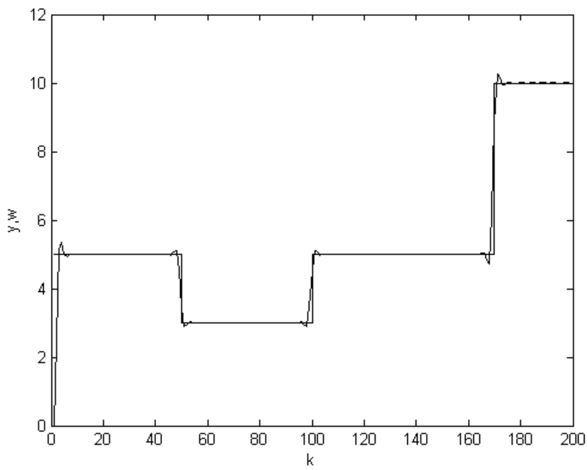

Fig. 7 Predictive control without disturbance $\lambda = 0{,}01$

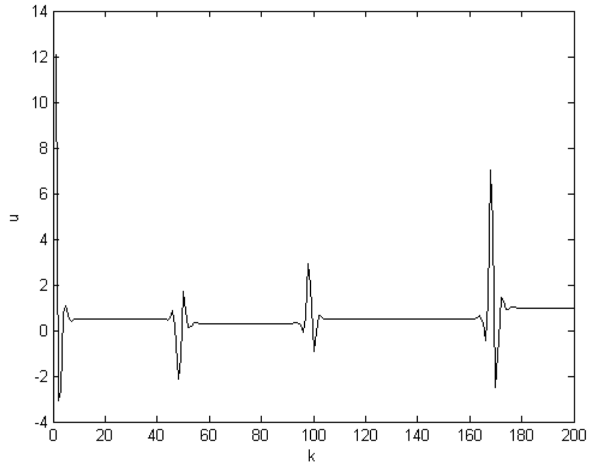

Fig. 8 Predictive control without disturbance $\lambda = 0{,}01$-manipulated variable

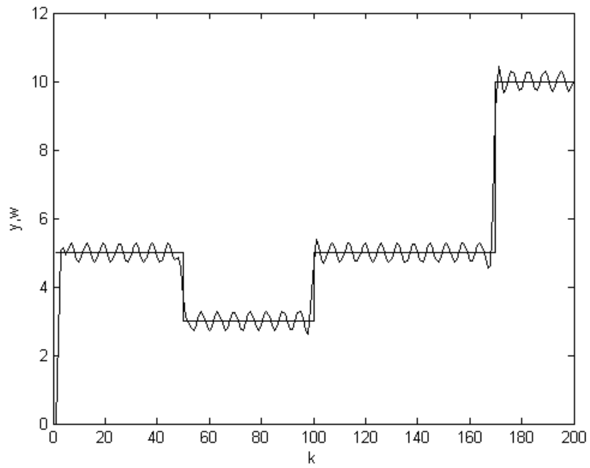

Fig. 9 Predictive controller $\lambda = 0{,}01$- control with disturbance without disturbance rejection

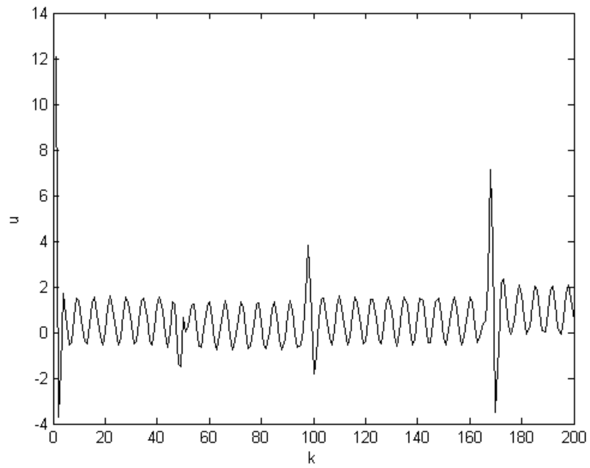

Fig. 10 Predictive controller $\lambda = 0{,}01$- control with disturbance without disturbance rejection-manipulated variable

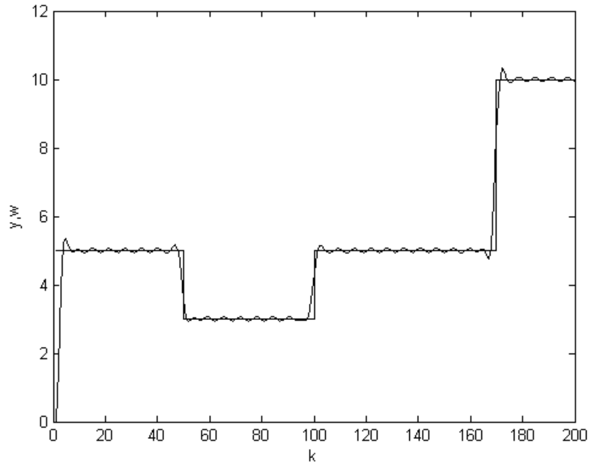

Fig. 11 Predictive controller $\lambda = 0{,}077$ - control with disturbance with disturbance rejection

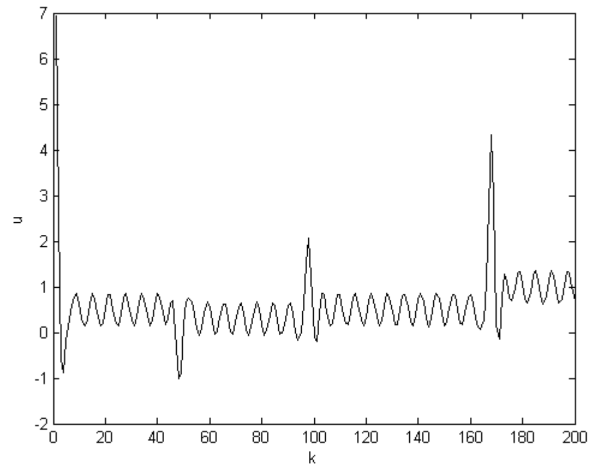

Fig. 12 Predictive controller $\lambda = 0{,}077$ - control with disturbance with disturbance rejection-manipulated variable

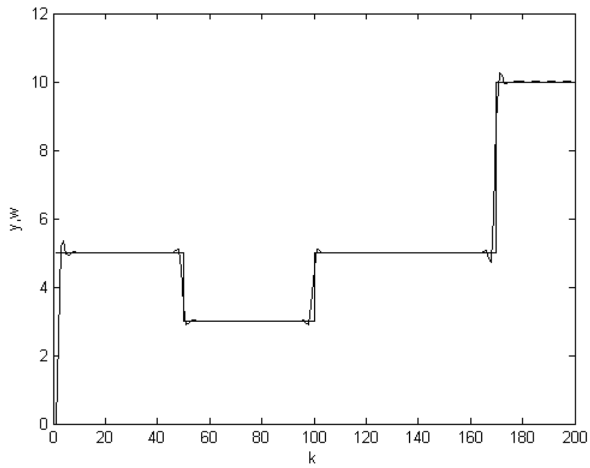

Fig. 13 Predictive controller $\lambda = 0{,}01$- control with disturbance with disturbance rejection

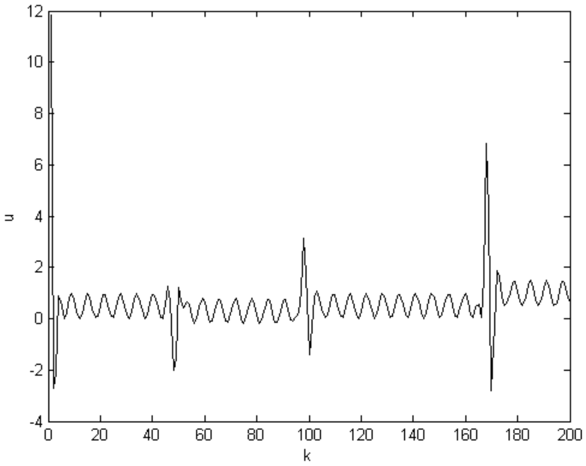

Fig. 14 Predictive controller $\lambda = 0{,}01$ - control with disturbance with disturbance rejection-manipulated

Table. 1 Control Quality Criteria

Controller	$\sum e^2$	$\sum \Delta u^2$
Polynomial	115,04	64,79
Predictive $\lambda = 0{,}077$	45,32	64,79
Predictive $\lambda = 0{,}01$	37,12	271,03

7 Conclusions

Two different control algorithms which enable suppression of measurable disturbances were proposed and compared. If a controller based on polynomial methods is applied then for each shape of the disturbance a different controller must be derived. For the predictive controller it is possible to put into a general prediction equation an arbitrary disturbance. The polynomial controller for sinusoidal disturbance was derived and performances of both controllers were compared by simulation. The simulation results proved that both controllers can be successfully applied for disturbance suppression. According to the chosen control quality criteria better performance has the predictive controller. On the other hand the controlled variable has slightly oscillatory character when using the predictive controller. The oscillations can be suppressed by larger rate of changes of the manipulated variable, which is however often undesirable.

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