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Improvement of HVAC systems based on adaptive predictive control

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Abstract. The paper considers the issue of approbation of adaptive predictive control for heating, ventilation and air conditioning systems, shows the possibility of improving the regulation processes by its application on example of ventilation system. The idea of control using predictive model is presented, the principles of control using MPC controller are noted, the controller structure and the criterion for choosing the optimal values of control signal are considered. The feature of adaptive predictive control is the presence of the mathematical model for control object, which accurately describes its behavior. The MPC controller determines the sequence of control signal values that provides the best predicted trajectory for controlled variable. The implementation of the MPC approach is shown on the example of supply VAV ventilation system of the classroom. In the considered ventilation system, the change of heat load for the room is compensated by the change of amount of supply air coming from the central supply ventilation unit at its constant temperature. To simulate ventilation system in the Simulink environment of the MATLAB application package, the block diagram was developed, and the Model Predictive Control Toolbox was used to synthesize the MPC controller. The study of transient processes in VAV ventilation system was carried out, transient process in the system without controller, with PID controller and MPC controller were compared. Comparison of the results showed that the use of the MPC controller makes it possible to improve the regulation process of thermal regime in the room by increasing the regulation quality.

1 Introduction

Heating, ventilation and air conditioning (HVAC) systems are one of the most important components of the design and development of industrial and administrative buildings and residential premises [1-5]. HVAC systems with the help of outdoor air supply maintain safe and comfortable conditions in them in terms of temperature, humidity, air velocity and cleanliness of the air environment.

The main tasks of control HVAC systems are [6-10]: creating and maintaining the microclimate within a building, construction or room that is comfortable for humans or

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animals and plants, as well as material objects (equipment, substances, products, works art, etc.); energy savings spent on creating and maintaining a microclimate; technological safety of the system and cost reduction for its operation.

To effectively control HVAC systems, it is necessary to conduct operational control of the microclimate parameters and the state of actuators parameters, as well as to form different modes of equipment operation [11-14]. So, in ventilation systems, one should choose the mode of operation in accordance with external and internal factors (temperature and humidity, room occupancy, concentration of harmful substances). Most often, such task occurs during the transition period, when the range of temperature changes varies within large limits. Automation and dispatching require the achievement of certain conditions: comfort, energy saving, technological safety, and lower operating costs. In this regard, the urgent task is to improve the regulation processes of HVAC systems.

2 Literature Review

Currently, new trends have emerged in the construction of automatic control systems [15, 16], which provide opportunities for improving the processes of managing the engineering equipment of buildings and premises. And here it should be noted the actively discussed adaptive predictive control of various technological processes, using predictive models - Model Predictive Control (MPC) [17, 18].

The idea of the MPC approach to adaptive feedback control is to find the sequence of optimal control actions that will provide the best predictable state of control object on the limited prediction horizon [19, 20]. The task of synthesizing adaptive control of nonlinear objects based on this approach consists of three main steps. First, the differential equations of nonlinear plant are represented by approximate linearized systems on each control interval. Further, using linearized models, predictive models are built based on the output signals of control object for the certain number of steps forward. And at the last stage, based on predictive models, the quality functional is minimized according to the quadratic programming algorithm to determine the optimal control action on the system.

The MPC approach has proven itself well in various areas of control of nonlinear objects, including in solving problems of controlling the thermal regime of buildings [21, 22]. The main advantages of the MPC approach include the fact that the optimal controller, the synthesis of which was carried out according to this approach, ensures the absence of static error in the system, the fulfillment of the required restrictions on the control and output variables, as well as the achievement of compromise between robustness and the quality of regulation [23, 24]. At the same time, like most other optimal systems, it requires the control object model. Since the MPC approach implements the state feedback control law, and the control is considered and performed on a very short time interval, its important advantage is that approximate linear models can be used to synthesize the control system.

In this regard, it is of undoubted interest to approbation the MPC approach for control HVAC systems, its implementation on the specific example and comparing the regulation quality with traditional approaches, in particular, using PID controllers.

The purpose of this paper is to approbation the MPC approach for control HVAC systems and to substantiate the possibility of improving the regulation process its application on the example of ventilation system.

3 Research Methodology

To conduct research, we will consider the principles of control based on the MPC approach.

To illustrate the implementation of the MPC approach, let us imagine the HVAC system as a one-dimensional system, i.e. consider it as a control object (CO) with one output value y. We also assume that the automatic control system (ACS) perceives one input action (signal) and one perturbation action. Then the ACS with the MPC controller can be represented by the structural scheme on Fig. 1. On fig. 1 are marked: g – setting input (signal); f – the perturbation action; u – the control input (control signal); W_u – the transfer function for CO on the control signal; W_f – the transfer function for CO on the perturbation; y – the output (controlled) parameter (variable); ε – the control error, $\varepsilon = g - y$.

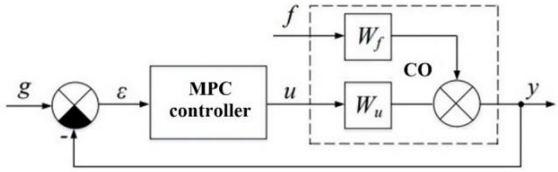

Fig. 1. The structural scheme of ACS with MPC controller.

Let us consider the principles of adaptive predictive control based on the MPC controller. Let there be a control action (signal) $u(t)$ on the control object and output controlled variable $y(t)$. The input action (signal) $g(t)$ is the desired value (dependence) of change for controlled variable. The system is considered at discrete times, i.e., only at times $t = k\Delta T$, where ΔT – the quantization period and k – the integer.

The main feature of adaptive predictive control is the presence of the mathematical model for control object, which accurately describes its behavior. Presence of the adequate mathematical model for control object makes it possible to predict the values of controlled variable for the certain number of steps ahead. On Fig. 2, the values of controlled variable $y(t)$ predicted at the time t are denoted by $\hat{y}(t)$. The prediction horizon is built for the certain number of steps N_p.

The predicted trajectory of the controlled variable will depend on the future values of control action $u(t)$, which are formed using the MPC controller. On fig. 3 shows the structural scheme of MPC controller. The controller includes the predictive model of control object (OC) and the optimizer.

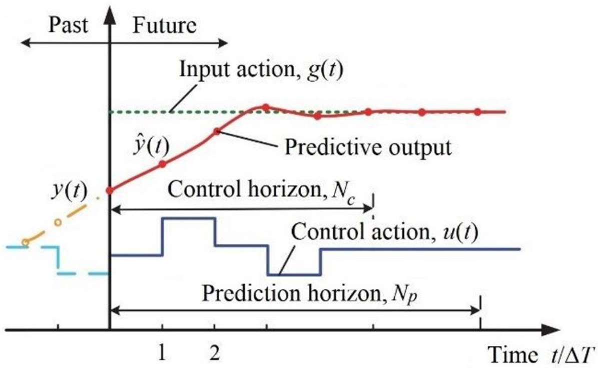

Fig. 2. The adaptive predictive control.

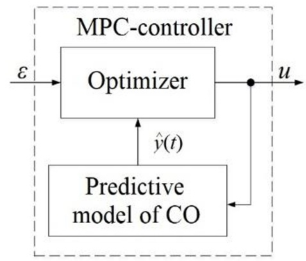

Fig. 3. The structural scheme of MPC controller.

The essence of adaptive predictive control is to determine by the MPC controller the values sequence of control signal $u(t)$, which will provide the best predicted trajectory for the controlled variable $y(t)$. The length of sequence N_c for calculated control actions $u(t)$ is a fixed value and is called the control horizon.

The necessary values sequence of control action is established by solving the optimization problem. The choice of the best trajectory for controlled variable is determined by the indicator of regulation quality, which is taken as the square of the mismatch between predicted output variable and input action (desired trajectory) $g(t)$. The change of the magnitude for control signal is also evaluated. Thus, to select the optimal values for control signal $u(t)$, the MPC controller seeks to minimize the following functional

$$J = Q\sum_{i=k}^{k+N_p}\left(y(i)-g(i)\right)^2 + R\sum_{i=k}^{k+N_c}\left(u(i)-u(k)\right)^2, \tag{1}$$

where Q and R – weight coefficients (for dimensionless variables they are usually assumed to be the same); $k = 1, 2, 3…$ – integer corresponding to the current moment in time; N_p – number of steps for which the forecast of the behavior for controlled variable $y(t)$ is built (prediction horizon); N_c – length of the sequence of future values of the control signal $u(t)$ (control horizon).

After applying the calculated optimal control action u(t) to control object, at the next step, the whole procedure is repeated again, taking into account the newly received information. To implement adaptive predictive control in the MATLAB application package, there is Model Predictive Control Toolbox [25, 26] for designing and modeling MPC controllers.

It should be noted that the above method for controlling ventilation systems based on the MPC approach can be generalized to multidimensional ACS and systems with several input and perturbation action.

4 Results

We will show the implementation of the MPC approach for control of HVAC systems using the example of the supply ventilation system VAV (Variable Air Volume) [27] in the classroom (Fig. 4) in the autumn-spring period, which maintains the given temperature regime T(t) in the room by changing the volume of supplied heated air. In the considered VAV ventilation system, the change of heat load of the room is compensated by the change of amount of supply air $G(t)$ coming from the central supply ventilation unit at its constant temperature.

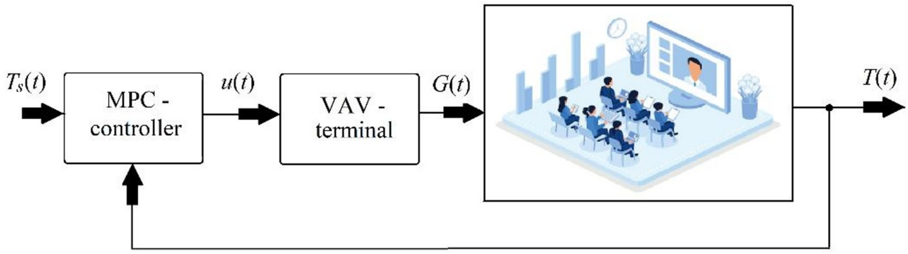

Fig. 4. The supply VAV ventilation system for classroom.

The main element of VAV ventilation system is the VAV terminal (Fig. 5), which is also called the VAV regulator or VAV valve. The purpose of the VAV terminal is to maintain the specified supply or exhaust air flow rate, the required value of which is determined by the value of the external control signal (influence) 1 (Fig. 6). This signal can be sent to the VAV terminal from temperature controllers installed in the building rooms, CO_2 sensors, motion sensors, time relays and other elements, as well as from the control device as part of automated microclimate control system in building or separate room. On the measuring elements of the VAV terminal (Pitot tube and piezometer) located in the ventilation channel, the pressure difference occurs, the value of which depends on the air flow rate (velocity) and is defined by the measuring transducer 2. Based on the value of the measured pressure difference and the cross-section area of the channel, the actual air flow rate is determined, the value of which is compared with the specified one. Based on the mismatch, the regulator 3 generates a signal to control the electric drive 4, which changes the position of the throttle shutter 5, which leads to change the aerodynamic resistance of the terminal and, consequently, to change the actual air flow rate.

Fig. 5. The VAV terminals of round and rectangular section.

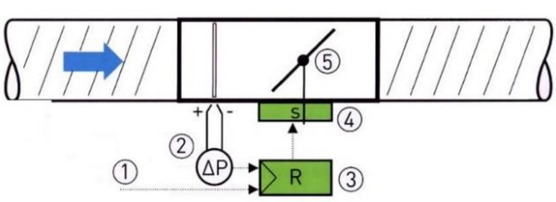

Fig. 6. The structural elements of VAV terminal.

On Fig. 6 are marked: 1 – external control signal (impact); 2 – pressure drop converter; 3 – regulator; 4 – electric drive of the throttle shutter; 5 – throttle shutter.

The study of VAV ventilation system was carried out according to the input action – the set temperature in the room $T_s(t)$. Using previously known methods [28, 29], based on experimental studies, the parametric identification of the ventilation system as control object was performed by the air temperature in the room $T(t)$ according to the mass flow rate of heated air $G(t)$ entering it. To identify the mathematical model, the capabilities of

System Identification Toolbox of the MATLAB application software package were used. The following transfer function for the room temperature on the mass air flow rates is obtained for dimensionless variables

$$W_{TG}(s) = \frac{e^{-54s}}{78s^2 + 320s + 1}, \tag{2}$$

where s – the Laplace variable.

Transfer function (2) for dimensionless deviations of variables was considered as the product of two typical links: the aperiodic link of the 2nd order and the delay link with time τ=54 s.

To simulate VAV ventilation system in the Simulink environment of the MATLAB application package, the block diagram was developed, shown in Fig. 7.

For the synthesis of MPC controller, Model Predictive Control Toolbox was used. To do this, the transfer function for control object was previously set in the MATLAB command line

```
>> plant=tf(1,[78 320 1],'IODelay',54);
```

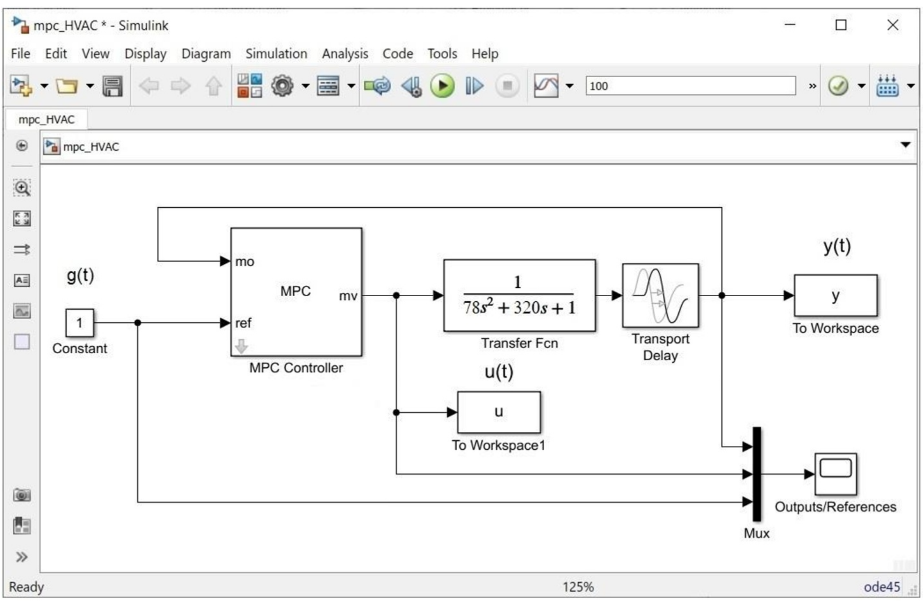

Fig. 7. The block diagram of ventilation system in Simulink.

Further, the following commands respectively designed the MPC controller and set its limitations

```
>> mpcobj=mpc(plant, 10, 100, 30);
>> mpcobj.MV=struct('Min',0,'Max',2);
```

The quantization period is set to ΔT =10 s, prediction horizon N_p=100 steps, control horizon N_c=30 steps. The minimum value of control signal $u(t)$ is 0, which corresponds to completely closed VAV terminal, and the maximum value is 2, which corresponds to the maximum amount of air at the outlet of VAV terminal, which is 2 times the average value of supply heated air flow rate $G(t)$ entering the room from the central ventilation system.

The results of calculation of transient processes in VAV ventilation system are shown in Fig. 8. Here, transient processes are compared in a system without controller, with speed of response optimized PID controller, and MPC controller. Comparison of results showed that the use of adaptive predictive control makes it possible to improve the regulation processes

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for VAV ventilation system by increasing the speed of response and reducing overshoot, which increases the accuracy for controlled parameters of microclimate in the room and the energy efficiency of system. The duration of transient process in system without controller was 1008 *s* (16.8 *min*), with PID controller 512 *s* (8.5 *min*), with MPC controller 262 *s* (4.2 *min*). When using MPC controller, there is practically no overshoot of the system, which does not lead to overheating when the room temperature rises above the set one, and this eliminates additional heat losses.

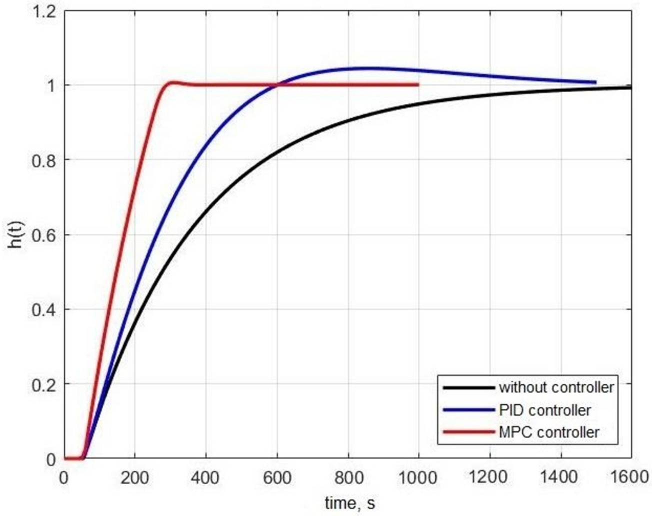

Fig. 8. The transient processes in ventilation system.

Regarding the issue of energy efficiency, we note that the VAV ventilation system operates at total air flow rate less than necessary for the total maximum heat load. This provides the reduction in energy consumption while maintaining the desired indoor air quality.

It should be noted that adaptive predictive control has disadvantages associated with the need to compile accurate and adequate mathematical models of control object. It is not always possible to create adequate mathematical model of ventilation system, and the more complex mathematical model of control object, the more computing power is needed to implement the MPC controller. Adaptive predictive control requires significant computational resources when controlling ventilation systems with several adjustable parameters and perturbations, since the optimization unit and the predictive model must work synchronously with the controlled process, and they practically cannot be divided into two independent subtasks. However, the modern development of microprocessor technology makes it possible to provide programmable controllers with the speed of response and memory required to implement adaptive predictive control algorithms based on MPC controllers in real time.

The conducted studies convincingly show that the use of MPC controller makes it possible to improve the regulation processes in VAV ventilation systems by increasing the speed of response and reducing overshoot, which improves the regulation quality of microclimate parameters and perfects the operational characteristics of ventilation systems.

5 Conclusions

Thus, the paper considers the issue of approbation of adaptive predictive control for HVAC systems and shows the possibility of improving the regulation processes by its application on the example of a ventilation system.

The idea of control using predictive model is presented, the principles of control using MPC controller are noted, the controller structure and the criterion for choosing the optimal values of control signal are considered. The feature of adaptive predictive control is the presence of the mathematical model for control object, which accurately describes its behavior. The MPC controller determines the sequence of control signal values that provides the best predicted trajectory for controlled variable.

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