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CONTROL OF THE LABORATORY HELICOPTER SIMULATOR

J. Macháček, L. Havlíček

University of Pardubice, Faculty of Electrical Engineering and Informatics

Department of Process Control, Nám. Čs. Legií 565, 532 10 Pardubice

Phone +420 466 037 122, e-mail jiri.machacek@upce.cz

Abstract: The laboratory helicopter simulator is a nonlinear two inputs - two outputs system with significant cross-coupling. The papers deals with control of vertical angle, where the controlled variable was the position angle and the manipulated variable was main motor voltage. The methods of control with PID controller, IMC controller and self-tuning adaptive controller were designed and tested. The control algorithms were used for tracking of the reference values and rejection of disturbances (moving of the tail rotor).

Keywords: Helicopter simulator, PID controller, IMC controller, self-tuning controller

1 INTRODUCTION

The real laboratory physical models are significant part of control engineering education. Control of real physical models opens many problems, which are hidden by computer simulation (static and dynamic properties sensors or actuators, immeasurable disturbances, hardware and software tools for the connection between system and computer, problems with sampling by real-time experiments, etc). Those real physical models are then closer to real industrial systems.

Laboratory system with twin rotor (helicopter simulator) is often used for laboratory education. This laboratory equipment produce *e.g.* firms Humusoft, Feedback or Bytronic. The system described in this paper was designed and realized in the Department of Process Control, University of Pardubice.

The helicopter is a nonlinear two inputs - two outputs system with significant cross-coupling. Many tasks may be realized on this system from the easy measurement of both static and dynamic characteristics to the multivariable control.

The aim of this paper is to give some suggestions for simple student's laboratory tasks on the one-dimensional control of vertical angle with fixed horizontal position. The paper includes the measurement of both step and frequency responses, the model building from identification results and controller design. The system was controlled by PID, IMC and adaptive discrete STC controllers.

2. SYSTEM DESCRIPTION

The system consists of two propellers driven by DC motors (Fig.1). The movable part has two degrees of freedom. The axes of rotation are perpendicular. The position angles (elevation and azimuth) are influenced by the rotation of propellers. The system can freely rotate around the vertical axis by about 215 degrees and the horizontal axis about 90 degrees. Both angles are measured by sensors and the angular velocities of the rotors by tacho-generators. DC motors are driven by power amplifiers with voltage in the range from 0 to 5 V. The main motor rotation is possible in one direction only, whereas the tail rotor may rotate in both directions. The model is connected with computer by NI USB – 6009 data acquisition device. The PC is equipped with the MATLAB and SIMULINK software along with the tools to perform measurements on the system and to implement controllers in real-time. Detailed description of the system can be found in Havlíček (2010). The paper deals with the control of vertical angle, where the controlled variables was the position angle and the manipulated variable was main motor voltage.

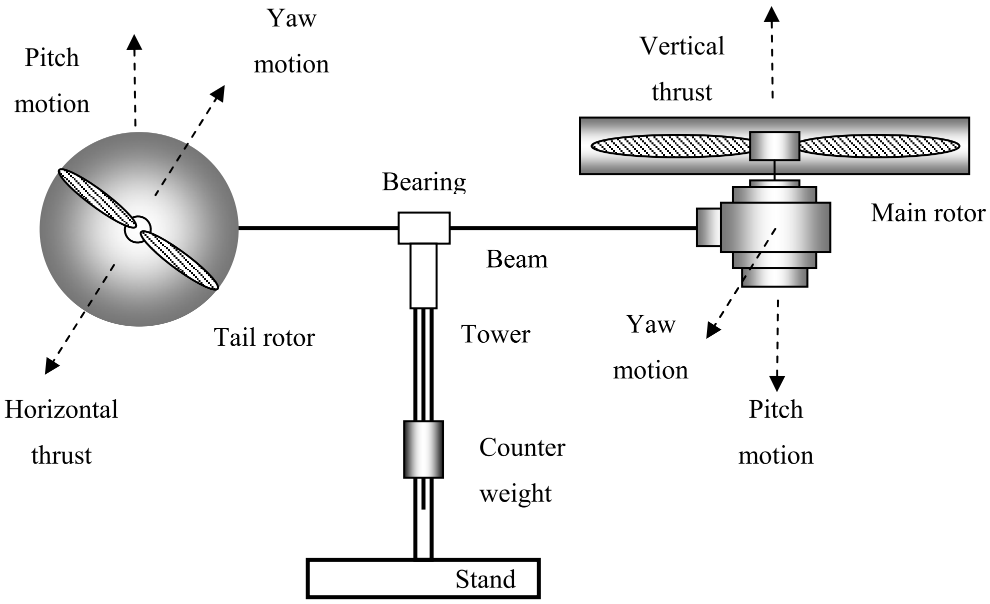

Fig. 1. - Twin rotor system

3. PROPERTIES OF MAIN ROTOR SYSTEM

Input of the main rotor system is the voltage on motor in range from 0 to 5 V and output is vertical angel in range from 0 to 90°. The voltage 2.5 V was taken as a nominal input which corresponds to nominal output angle 29°. Next the values of the input and output variables were taken as deviations from these nominal points. The disturbance variable is presented by the rotation of the tail propeller. Following measurements on the system were performed: Static characteristic, step responses, frequency characteristic and experimental identification.

3.1 Static characteristic

The course of the measured static characteristic is given in Fig. 2. The system is nonlinear and its gain increase with input voltage.

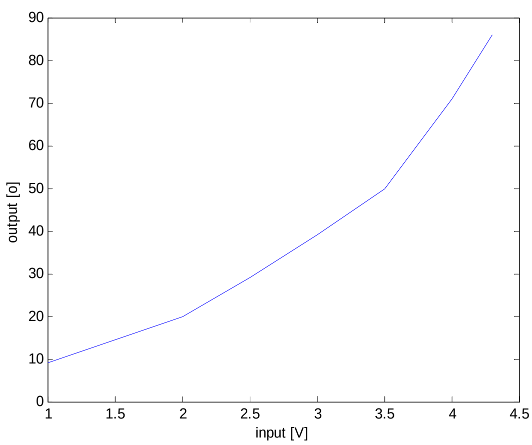

Fig. 2. Static characteristic

3.2 Step responses

The response on step voltage change was measured in three operating points – round about nominal value (step from 2 to 3 V), step for small voltage (from 1 to 2 V) and step for higher voltage (from 3 to 4 V). The all responses are shown in Fig. 3. The step responses change with operating points in accordance with course of the static characteristic.

3.3 Frequency response

The frequency response was measured for the nominal operating point and it is presented in Fig. 4. Maximum gain occurs by the frequency $\omega = 1.8\, s^{-1}$ where phase angle is $-\pi$.

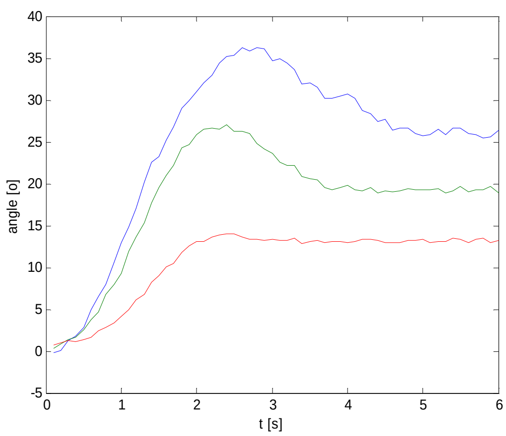

Fig. 3. Comparison of step responses (without time delay 1 s)

(red – step from 1 to 2 V, green – step from 2 to 3 V, blue – step from 3 to 4 V)

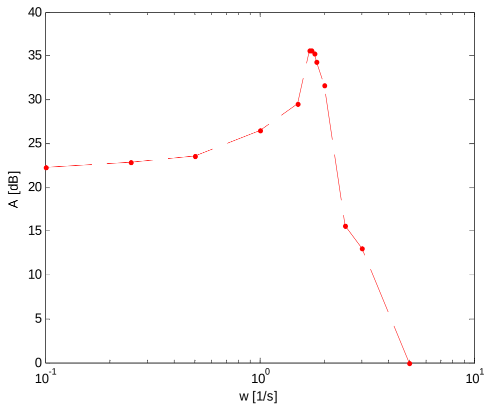

Fig. 4. Amplitude frequency response

3.4 *Model from experimental identification*

The sampling period was proposed with regard to speed of the data acquisition device during connection with MATLAB – Simulink. The model of STC controller is relatively complicated and the sampling period was hence chosen $T = 1$ s.

Structure of the model was proposed as the system of the second order with time delay 1 s. It is the simplest model which can ensures the overshoot of step response. The difference equation has the form

$$\begin{aligned} &y(k) + a_1 y(k-1) + a_2 y(k-2) = \\ &= z^{-1}\left[b_1 u(k-1) + b_2 u(k-2)\right] \end{aligned} \tag{1}$$

and its parameters were computed by the least-squares method, see *e.g.* Drábek *et al.* (1987). Several step responses close to the nominal values were evaluated and the following parameters were obtained:

$$\begin{aligned} a_1 &= -1.2784 \\ a_2 &= \ \ 0.5460 \\ b_1 &= \ \ 6.3608 \\ b_2 &= -0.6645 \end{aligned} \tag{2}$$

The model (1) with these parameters is the good approximation of dynamic behaviour of the identified system in given area.

4. SYSTEM CONTROL

Several methods were used for controller design. The controllers were realized in MATLAB – Simulink. All controllers were verified for reference tracking and rejection of disturbances (moving of the tail rotor).

4.1 *PID controller*

The PID controller in continuous form has transfer function

$$G_R(s) = r_0\left[1 + \frac{1}{sT_i} + sT_d\right] \tag{3}$$

and its parameters were designed according to frequency Ziegler-Nichols method - Ziegler *et all.* (1942). The ultimate (critical) values were first measured for the sampling period T = 0.1 s: $r_{0k} = 0.0172$ and $T_k = 3.5\,s$. Hence controller parameters are

$$\begin{aligned} r_0 &= 0.6\, r_{0k} = 0.0103 \\ T_i &= 0.5\, T_k = 1.75\ s \\ T_d &= 0.125\, T_k = 0.4375\ s \end{aligned}$$

Response on the step changes of reference and on the influence of tail rotor moving (voltage 4.5 V in time 220 s) is given in Fig. 5.

The ultimate values changed when the sampling period is increased. For example the ultimate gain was r_{0k} = 0.0455 for T = 1 s and the ultimate period was $T_k = 6\,s$. But the PID controller designed from this values was not acceptable, as output variable oscillated. It was caused the nonlinear behaviour of plant. The ultimate values for the other operating point (u = 3.5 V; r_{0k} = 0.0212; T_k =5 s) gave good response (see Fig.6).

4.2 *IMC controller*

Internal Model Control (IMC) is an effective method of controller design, which requires limited computation - Morari *et al.* (1998), Macháček *et al.* (2004). The block diagram of IMC is shown in Fig. 7, where G is controlled process, G_M is process model and G_{RI} is controller.

The process model must be factorized on invertible G^- and noninvertible G^+ part:

$$G_M(s) = G^- G^+ \tag{4}$$

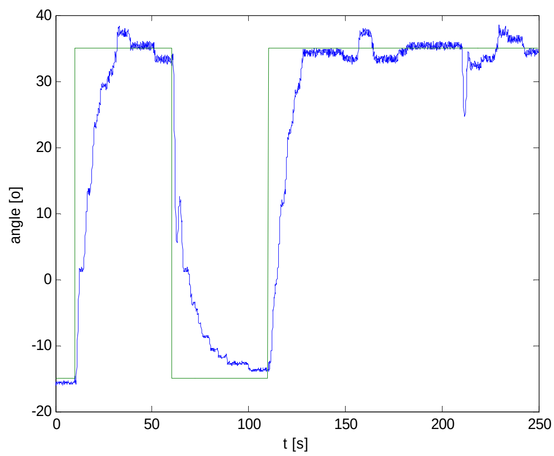

Fig. 5. Control process with PID controller (T = 0.1 s)

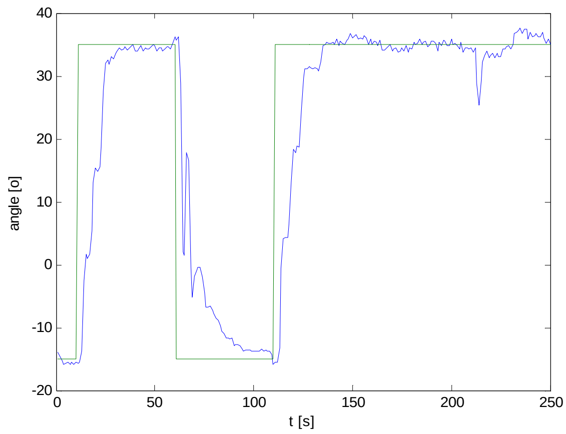

Fig. 6. Control process with PID controller ($T = 1$ s)

The controller includes the invertible part of process model. The noninvertible parts are time delay and the factors with right-half-plane zeros, which stay in closed loop transfer function. A linear filter can be added to make possible the controller realization:

$$G_f(s) = \frac{1}{(\tau_f s + 1)^r} \tag{5}$$

where τ_f is the select parameter for adjustment of the closed-loop dynamics and r is chosen according to model order. The controller is then in the form:

$$G_{RI}(s) = \frac{G_f(s)}{G^-(s)} \tag{6}$$

The all models with the exception of time delay may be inverted in our case. The filter (5) of second order with $\tau_f = 2\,s$ was chosen and its discrete transfer function for $T = 1$ s was

$$G_f(z) = \frac{0.0902z + 0.06446}{z^2 - 1.213z + 0.3679} \tag{7}$$

The course of experiment was the same as for the PID controller. The measured response is given in Fig. 8.

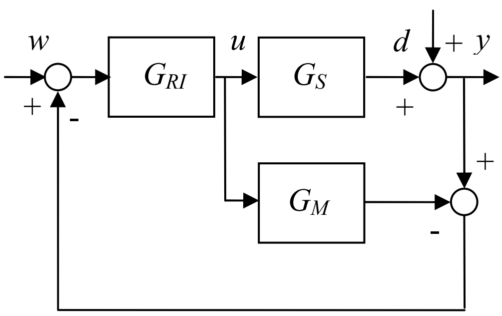

Fig. 7. Block diagram of IMC

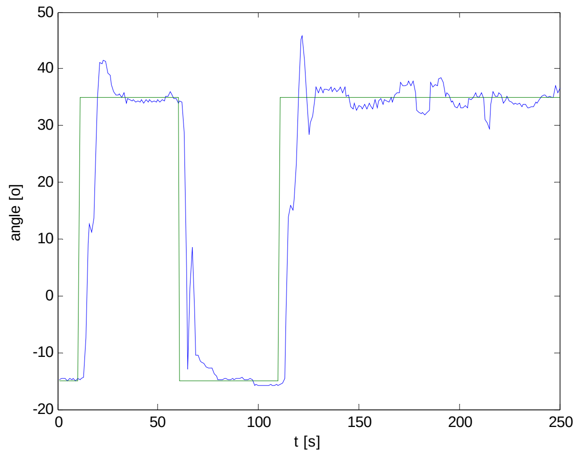

Fig. 8. Control process with IMC controller ($T = 1$ s)

The IMC controller is sensitive on the accuracy of model and control process quality was worse for great reference steps.

4.3 Self-tuning controller

Controllers with fixed parameters are often unsuited to nonlinear processes because their parameters change with operating conditions. One possible alternative for improving the quality of control for such processes is the use of adaptive control system. The approach to adaptive control, called self-tuning controller (STC), is based on the recursive identification of controlled system and subsequently on the design of optimal controller from identified parameters. The controller is digital and works with fixed sampling period T. More information about STC can be found *e.g.* in Bobál *et al.* (2005).

The recursive least squares method together with a forgetting strategy is used to estimate the process model parameters, as the part of the general control algorithm. The parameter vector $\boldsymbol{\Theta}$ for (k+*1*)-th time interval is estimated using the following recursive equations:

$$\hat{\boldsymbol{\Theta}}(k+1) = \hat{\boldsymbol{\Theta}}(k) + \boldsymbol{m}(k)[y(k+1) - \boldsymbol{\Phi}^T(k+1)\hat{\boldsymbol{\Theta}}(k)] \tag{8}$$

$$\boldsymbol{m}(k) = \boldsymbol{C}(k)\boldsymbol{\Phi}(k+1)[\varphi + \boldsymbol{\Phi}^T(k+1)\boldsymbol{C}(k)\boldsymbol{\Phi}(k+1)]^{-1} \tag{9}$$

$$\boldsymbol{C}(k+1) = \frac{1}{\varphi}[\boldsymbol{C}(k) - \boldsymbol{m}(k)\boldsymbol{\Phi}^T(k+1)\boldsymbol{C}(k)] \tag{10}$$

where φ is the forgetting factor $\varphi \le 1$.

The data vector $\boldsymbol{\Phi}$ has for the model of second order with time delay and offset form

$$\boldsymbol{\Phi}^T(k+1) =$$
$$= [-y(k) \quad -y(k-1) \quad u(k-d) \quad u(k-d-1) \quad 1]$$

and the parameter vector is then

$$\Theta^T(k+1) = [a_1 \quad a_2 \quad b_1 \quad b_2 \quad \mathrm{c}]$$

The algorithm begins with diagonal matrix ***C***, which has the same values on its main diagonal (chosen 100) and an arbitrary initial parameter vector (chosen all 1).

The IMC controller was chosen as the control part of the adaptive algorithm. The on-line identification and IMC controller design are repeated in every sampling time. The model from experimental identification is used for controller design. The transfer functions of model G_M (from Eq. 1), controller G_{RI} (Eq. 6) and filter G_f (Eq. 7) are taken in discrete form with sampling period $T = 1$ s.

The controller was realized directly in Simulink, which can to work (from the version 4) with signals type matrix - Dušek *et al.* (2004). Real time toolbox was then not need to use. The blocks from Simulink Library as *Selector* (selects or reorders specified elements of multidimensional signal) or *Reshape* (changes the dimensions of a vector or matrix signal) were used for modelling identification and control algorithms. Block scheme of the whole adaptive controller is in Fig.9.

Response of the system with STC IMC regulator on the same signals as for the PID and IMC controllers is given in Fig. 10.

5. CONCLUSIONS

The control of the vertical angle was realised with several controllers. The control algorithms were used for tracking of the reference values and rejection of disturbances (moving of the tail rotor). Direct comparison of used methods by some numerical criterion is not suitable. Firstly the controlled system is nonlinear and control process quality depends on operating point. The STC controller is the best method from this objective. In the second place the disturbances are larger then differences among methods.

All controllers gave relatively good control process. The influence of the tail rotor moving on the process control was small. Self tuning controller had better tracking of reference, but worse rejection of disturbances. The results of this work will be used for laboratory education.

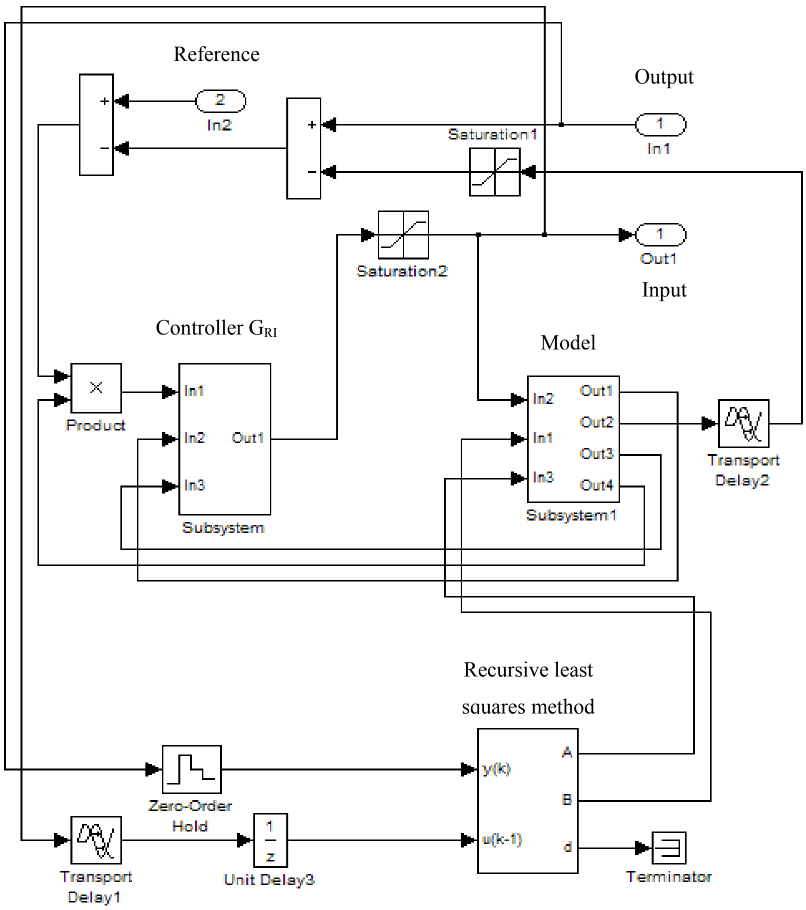

Fig. 9. Block scheme the whole adaptive controller

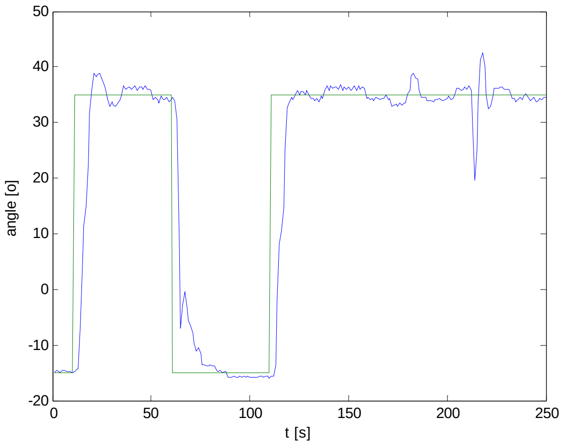

Fig. 10. Control process with STC controller

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