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ROBUST CONTROL DESIGN FOR THERMO-OPTICAL PLANT UDAQ28/LT

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Abstract: In this paper design of robust control for thermo-optical plant uDAQ28/LT is presented. Decentralized approach for controller design is used. For modeling real and complex perturbation input multiplicative uncertainty was applied and robust stability condition was derived in terms of the M-delta structure.

Keywords: decentralized control, PID controller, robust stability, M-delta structure, UDAQ28/LT.

1 INTRODUCTION

A control system is robust if it is insensitive to differences between the actual system and the system model used to design the controller. These differences are referred to as model/plant mismatch or simply model uncertainty. Uncertainty in the system model may have several sources: imperfect measuring devices, variations of the linear model parameters due to nonlinearities or changes in the operating conditions, only approximate knowledge of some parameters etc. To deal with it the uncertainty model is used (Skogestad and Postlethwaite, 1996), (Kozakova and Vesely, 2003); then, instead of examining a single plant model, the behavior of a class of models is considered. Let $\tilde{G}(s) \in \Pi$ be any member of a set of possible plants Π and $G_0(s) \in \Pi$ be the nominal model of the plant. A simple uncertainty model is obtained using unstructured uncertainty, i.e. a full complex perturbation matrix Δ with dimensions compatible with the plant, and satisfying $\sigma_M(\Delta(j\omega)) \le 1$. Where $\sigma_M(\bullet)$ denote maximal singular value of $\bullet$.

This paper deals with the input-output pairing and frequency domain modeling of uncertain plants. Input multiplicative uncertainty is applied to allow robust stability analysis and conditions guaranteeing stability of the uncertain plant for all perturbations in the uncertainty set are derived using the Generalized Nyquist stability theorem and the $M-\Delta$ structure stability conditions.

2 PRELIMINARIES AND PROBLEM FORMULATION

Thermo-optical plant uDAQ28/LT (Fig. 1) is multivariable system with three manipulated inputs and seven measurable outputs (Fig. 2).

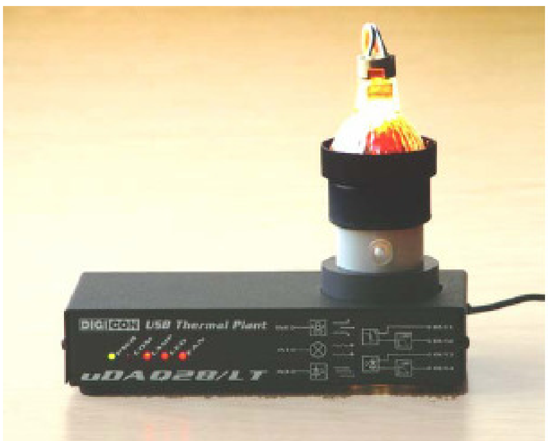

Fig. 1 Thermal plantuDAQ28/LT

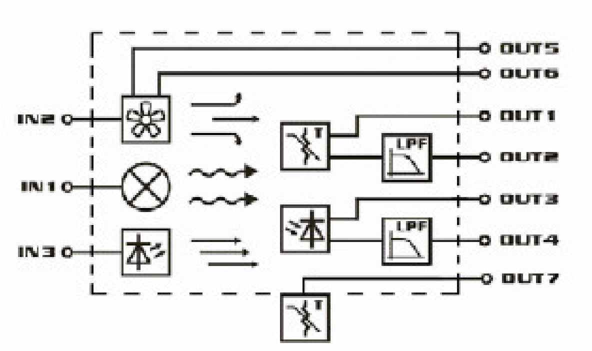

Fig.2 Basic electric diagram of thermo-optical plant uDAQ28/LT

System has three manipulated inputs: bulb voltage (0-5V) which represents heater and light source, fan voltage (0-5V) which can be used for temperature decreasing and voltage of led diode (0-5V) which represents another source of light.
On the output is possible to measure seven variables: temperature insight the system (direct or filtrated), outsight temperature, light intensity (direct or filtrated), fan velocity and fan current.

Problem formulation:
Find input-output pairing which can be used for the uncertain system identified in several working points and design the decentralized PID controller which will guarantee closed-loop robust stability within the uncertainty range specified by the given working points.

3 THEORETICAL RESULTS

3.1 *Input-output pairing*

First step, before the controller synthesis can be done is choice of manipulated inputs and measurable outputs.
Fan current and fan velocity depends only on fan voltage and other manipulated inputs has no influence on this outputs. Because the aim is control the multivariable system, temperature and light intensity were chosen as measurable outputs. Thermal process is relative slow process and temperature settling time is several minutes so direct measure of temperature without filtration can be chose as first output. Contrariwise the light intensity is very quick with settling time 0.6s so in this case measuring with first order filter with time constant 20s was selected.
Three inputs and two outputs are available but standard decentralized methods are designed for square matrices (equal numbers of inputs and outputs) so it is desirable to eliminate one input. Bulb voltage can not be removed because it is unique heater so two possibilities of input combination are available: bulb and led diode voltage or bulb and fan voltage. Static characteristic for both cases are shown in Fig. 3 and Fig. 4.

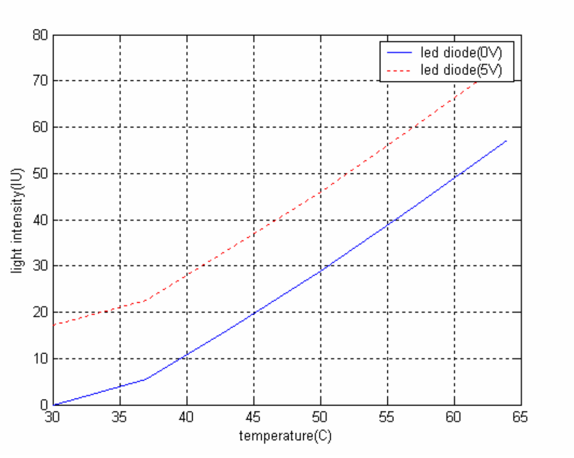

Fig. 3 Static characteristic (inputs bulb and led voltage)

In Fig. 3 is static characteristic with minimum led voltage (blue line) and maximum led voltage (red line). With led voltage can be only light intensity increased therefore input-output pairing is led voltage - light intensity and bulb voltage - temperature. With this input-output combination can plant be controlled if working points are situated in area between blue and red line.

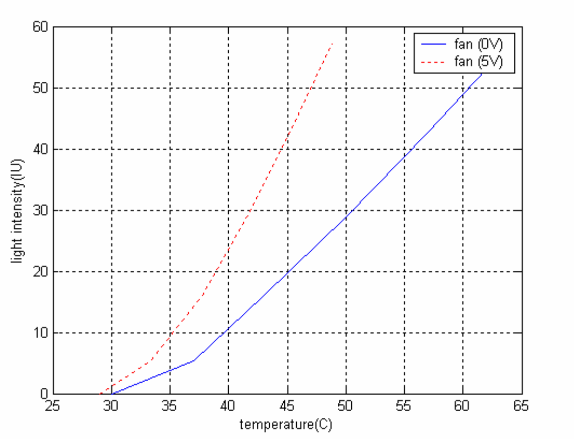

Fig. 4 Static characteristic (inputs bulb and fan voltage)

In Fig. 4 is static characteristic with minimum fan voltage (blue line) and maximum fan voltage (red line). Fan voltage has no influence on light intensity only temperature can be decreased therefore input-output pairing is bulb voltage - light intensity and fan voltage - temperature. With this input-output combination can plant be controlled if working points are situated in area between blue and red line.

3.2. *Design of robust decentralized controller*

Consider the uncertain plant modeled using the input multiplicative form of uncertainty (Fig. 5)

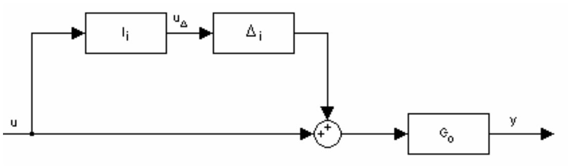

Fig. 5 Input multiplicative uncertainty

According to Fig. 5, the uncertain plant is described as follows

$$\tilde{G} = G_0 (I - l_i \Delta_i) \text{ with} \mid \Delta_i (j\omega) \mid \leq 1 \ \forall \omega \quad (1)$$

Rule for computing the corresponding weighting function as follows

$$l_i(\omega) = \max_{\tilde{G} \in \Pi} \sigma_M [G_0^{-1}(G_0 - \tilde{G})] \quad (2)$$

The set of perturbed plants is given as a set of transfer functions matrices G_k, $k = 1,2,\ldots,N$ identified in N different working points. In such case (2) modifies to

$$l_i(\omega) = \max_k \sigma_M [G_0^{-1}(G_0 - G_k)] \quad k = 1,2,\ldots,N \quad (3)$$

To derive the related robust stability condition, the feedback system with the input multiplicative uncertainty in Fig. 6 is to be transformed into the *M-Δ* structure (Fig. 7) and the robust stability theorem (Skokestad and Postlethwaite, 1996) is to be applied.

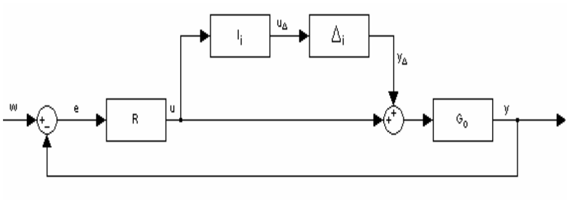

Fig. 6 Feedback system with the input multiplicative uncertainty

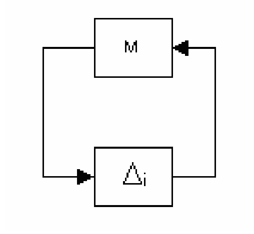

Fig. 7 M-Δ structure

Theorem 1 (Robust stability for unstructured perturbations)

Assume that the nominal system $M(s)$ is stable and the perturbation $\Delta_i(s)$ is stable. Then the $M - \Delta_i$ system in Fig. 7 is stable for all perturbations satisfying $\sigma_M[\Delta(j\omega)] \leq 1$ if and only if $\sigma_M[M(j\omega)] < 1 \quad \forall \omega$.

Fro the input multiplicative uncertainty case the matrix M is computed as follows

$$M = l_i R G_0 (I + G_0 R)^{-1} = l_i M_0 \quad (4)$$

and

$$M_0 = R G_0 (I + G_0 R)^{-1} \quad (5)$$

According to the Theorem 1 the robust stability condition $\sigma_M[M(j\omega)] < 1$ modifies to

$$\sigma_M [M_0(j\omega)] < \frac{1}{|l_i(\omega)|} \quad (6)$$

Relations (3), (5) and (6) will be applied in the design of a robust decentralized controller for thermo-optical plant uDAQ28/LT

4 CASE STUDY

For robust controller design input combination bulb and fan voltage was chosen. The bulb voltage will be used to light intensity control and fan voltage will be used to temperature control. But with the fan voltage it is not possible to increase temperature so the temperature will be increased trough the interaction from bulb voltage.
Opposite pairing is not considered because fan voltage has no influence on light intensity.

The system was identified in three working points WP_1 (42, 16), WP_2 (36.5, 5.5) and WP_3 (39.5, 10) yielding following transfer function matrices

WP (temperature, light intensity)

1st working point:

$$G_1(s) = \begin{bmatrix} \dfrac{0.936s - 2.2}{4s^2 + 105.6s + 1} & \dfrac{4.543s + 5.357}{7.14s^2 + 216.357s + 1} \\ 0 & \dfrac{-2.7s + 10.93}{0.775s^2 + 21.434s + 1} \end{bmatrix}$$

2nd working point:

$$G_2(s) = \begin{bmatrix} \dfrac{0.207s - 0.41}{0.36s^2 + 12.887s + 1} & \dfrac{9.577s + 5.339}{7.692s^2 + 358.615.s + 1} \\ 0 & \dfrac{-3.137s + 10.25}{0.392s^2 + 21.349s + 1} \end{bmatrix}$$

3rd working point:

$$G_3(s) = \begin{bmatrix} \dfrac{3.761s - 2.132}{21.368s^2 + 160.256s + 1} & \dfrac{7.78s + 5.002}{5.903s^2 + 241.558s + 1} \\ 0 & \dfrac{-1.152s + 10.616}{1.505s^2 + 30.489s + 1} \end{bmatrix}$$

For these three working points the mean value parameter nominal model was calculated

$$G_0 = \begin{bmatrix} \frac{1.635s - 1.581}{8.576s^2 + 92.91s + 1} & \frac{7.3s + 5.233}{6.912s^2 + 272.2s + 1} \\ 0 & \frac{-2.33s + 10.6}{0.891s^2 + 24.42s + 1} \end{bmatrix}$$

The uncertainty weight function computed according to (3).is plotted in Fig. 8.

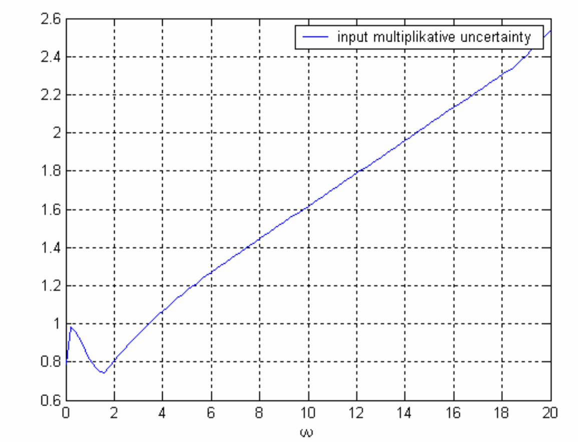

Fig. 8 weighting function for the input multiplicative uncertain

For the nominal model a decentralized controller $R(s) = diag\{R_i(s)\}_{i=1,2}$ consisting of local PID controllers $R_i(s) = k + \frac{k_i}{s} + k_d s$ was designed using SIMC (simple analytic rules for PID controller tuning) (Skogestad, 2003). Local controllers were designed from diagonal subsystems which were transformed into second-order time delay form.

$$g(s) = \frac{k}{(T_1 s + 1)(T_2 s + 1)} e^{-\theta s} \qquad (7)$$

Following tuning rules are used for controller calculation

$$K_c = \frac{1}{k} \frac{T_1}{(\tau_c + \theta)}, T_i = \min\{T_1, 4(\tau_c + \theta)\}, T_d = T_2$$

where τ_c is tuning parameter.

First subsystem of nominal model transformed into second-order time delay form:

$$g_1(s) = \frac{-1.58}{(92.81s + 1)(0.0924s + 1)} e^{-1.03s} \qquad (8)$$

Tuning parameter was chosen $\tau_c = 8.5$, resulting controller

$$R_1(s) = -5.92 - \frac{0.15}{s} - 0.55s \qquad (9)$$

Second subsystem of nominal model transformed into second-order time delay form:

$$g_2(s) = \frac{10.6}{(24.38s + 1)(0.0365s + 1)} e^{-0.22s} \qquad (10)$$

(10)

Tuning parameter was chosen $\tau_c = 15$, resulting controller

$$R_2(s) = 0.67 + \frac{0.049}{s} + 0.024s \qquad (11)$$

Note:
Parameters of R_1 controller are negative because gain of first subsystem is negative too.

Nominal closed-loop stability has been verified by calculating roots of the closed-loop characteristic polynomial $\det[I + G_0(s)R(s)]$; the resulting set Λ of closed-loop eigenvalues proves the nominal stability.

$$\Lambda = \{-0.0467, -0.0506, -0.0489 \pm 0.1212i, -10.8215, -27.3831\} \qquad (12)$$

Robust stability condition (6) is verified in Fig. 9. Indeed, the blue line corresponding to $\sigma_M[M_0(j\omega)]$ lies below the red line corresponding to $\frac{1}{|l_i(\omega)|}$ over the whole frequency range considered. Robust stability has been verified also by real measurements in each working point (Fig. 10-12).

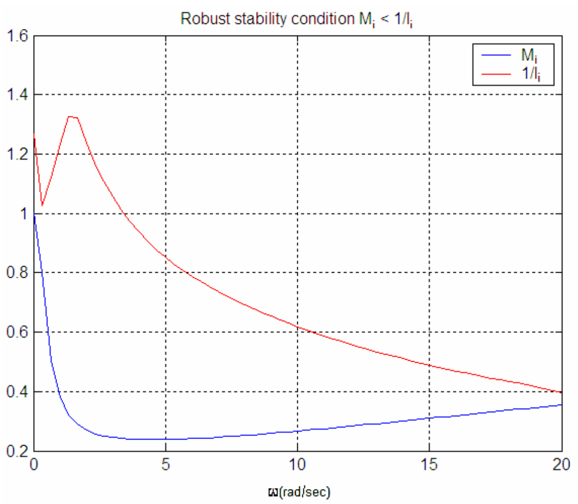

Fig. 9 Verification of the robust stability condition

$$\sigma_M[M_0(j\omega)] < \frac{1}{|l_i(\omega)|}$$

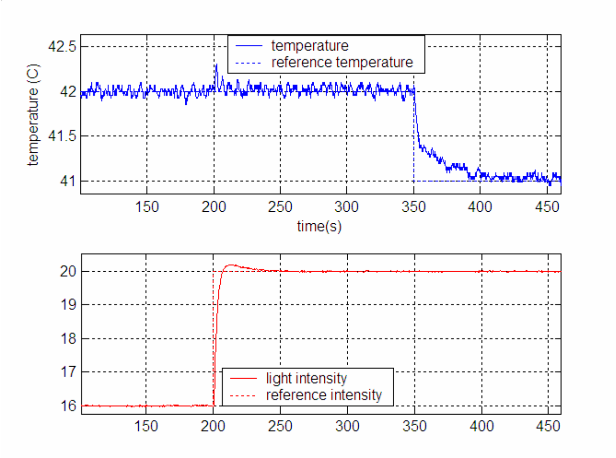

Fig.10 Step response for light intensity a temperature in WP_1

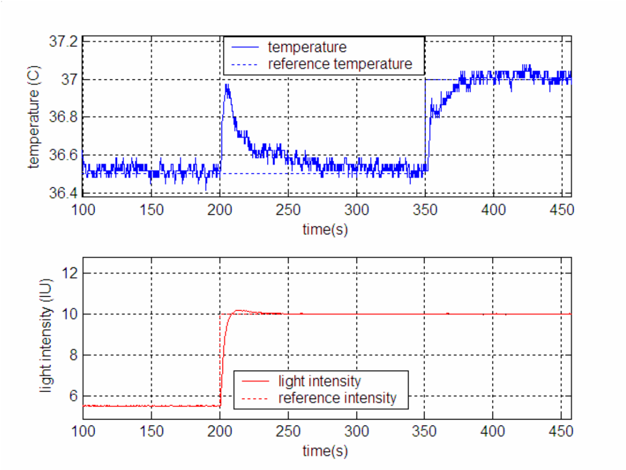

Fig.11 Step response for light intensity a temperature in WP_2

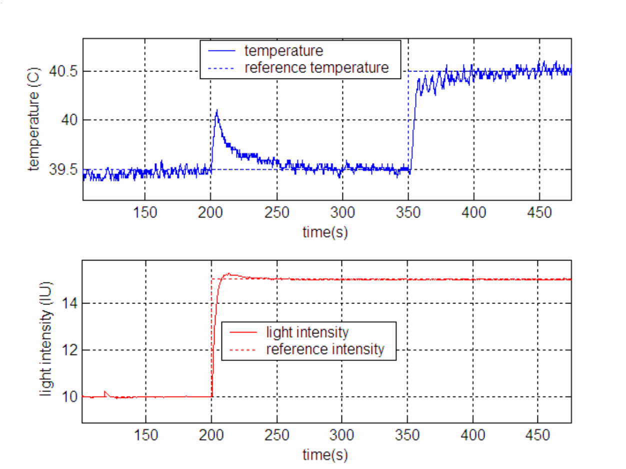

Fig.12 Step response for light intensity a temperature in WP_3

Simulations proved that system is stable in all working points with relative good performance. Light intensity step responses are with small overshot less than 5% and temperature practically without any overshot. Also the effect of interaction in time when step change of light intensity was done is apparent.

5 CONCLUSIONS

In this paper design of robust control for thermo-optical plant uDAQ28/LT was presented. For modeling real and complex perturbation input multiplicative uncertainty was applied. Robust stability conditions guaranteeing stability of the whole set of uncertain plants were derived. Theoretical results have been verified by simulations directly on thermo-optical plant uDAQ28/LT.

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