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Relay Identification Analyzing Non-symmetrical Oscillations for Optical Plant

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Abstract: The paper deals with approximation of systems with the dominant first order dynamics by the Integrator Plus Dead Time (IPDT) model based on the analysis of the nonsymmetrical oscillations with possible offset arising typically under relay control. The analytical derivation is illustrated by results achieved by identification of optical plant. The results are experimentally verified by PI controller tuned using the identification results. Process parameters in various operating points are analyzed and the robutst controller tuning based on performance portrait analysis is employed.

*Keywords***:** relay identification, integrator plant, nonsymmetrical oscillations.

1. INTRODUCTION

The relay feedback test is very popular approach used in several commercial autotuners. The current research in this area was closely analyzed in (Tao Liu, Furong Gao 2009). There are two types of relay tests, unbiased and biased. When using the unbiased test the process gain can be highly deflorated by a load disturbance. Many relay feedback methods have been proposed to reject static disturbances (Hang, Åström, & Ho, 1993; Park, Sung, & Lee, 1997, 1998; Shen, Wu, & Yu, 1996). Their approaches bias the reference value of the relay on–off as much as a static disturbance (that must be known in advance), in order to achieve the same accuracy as in the case of no disturbance. Nevertheless none of these approaches can be applied to large static disturbance, of which the magnitude is bigger than that of the relay. By inserting a proportional integral (PI) controller behind the relay for the test, (Sung and Lee, 2006) proposed an identification method for application against large static disturbance, larger than the magnitude of the relay. The drawback of the method is given be necessity to tune an additional controller.

Another important question is related to the models used for approximating the plant dynamics. Almost 70 years ago, Ziegler and Nichols (Ziegler & Nichols, 1942) proposed to use the sustained oscillations for process dynamics characterization giving finally PID controller tuning, whereby the process dynamics approximation was equivalent to the use of the IPDT model. It is, however, well known that the method is appropriate also for dealing with many systems with more complicated and typically static dynamics. Several papers investigate the transition point when the designer should choose to use more complex models - the First Order Plus Dead Time (FOPDT) representing the first possible extension (Skogestad, 2003; Jones and Tham, 2004). Also Huba (2003) shows that for the relatively low ratio of the dead time and the plant time constant T_d / T_p it is enough to use the to Integrator Plus Dead Time (IPDT) approximations also for dealing with the FOPDT processes used in this paper. However, when using the IPDT approximation for the FOPDT process, the plant feedback that is around an operating point equivalent to a load disturbance will lead to assymmetrical behavior also in the case with symmetrical relay without additional load. So, in the relay identification this oscillation asymmetry is playing an important issue with respect to the precision of the whole approximation. For a noncompensated disturbance (including also the internal plant feedback around the operating point), the deformation of oscillations leads to increased influence of higher harmonics and to decreased precision of the identification both by using the describing functions method and the Fast Fourier Transform (FFT). The main advantage of constraining the plant approximation to the IPDT model

$$S(s) = K_s e^{-T_d s} / s \tag{1}$$

is that both the experiment setup and the corresponding formulas remain relatively simple and more robust against measurement noise than when using the FOPDT model. There is no need to tune the PI controller before the identification, or to use the PI controller with an additional anti windup circuitry.

Let us consider oscillations in the control loop with a relay with the output $u_r = \pm M$ and a piecewise constant input disturbance $v = const$. Then, the actual plant input will be given as a piecewise constant signal $u_A = \pm M + v$. Possible transients are shown in Fig. 2.

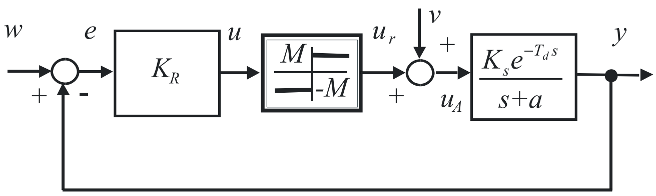

Fig. 1 Relay identification with nonsymmetrical plant input

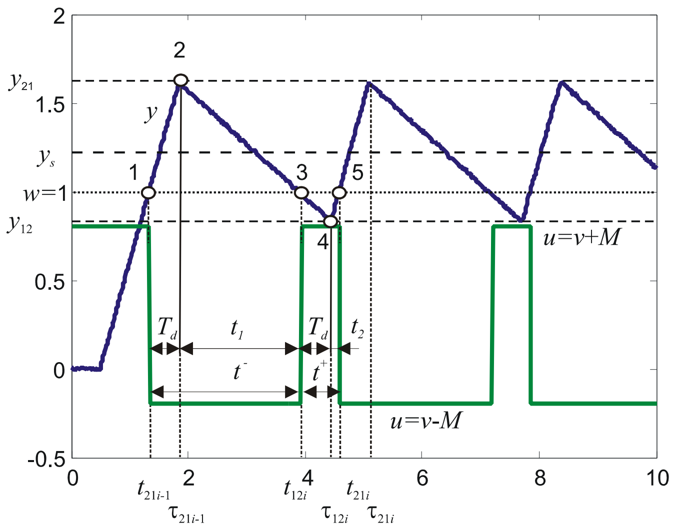

Fig. 2 Transients of basic variables of the loop in Fig. 1

By assuming relay switching from the positive relay output $u = M$ to the negative value $u = -M$ (point 1) at the time moment t_{21i-1}, due to the dead time the influence of the positive plant input $U_2 = (v + M)K_s$ will keep over interval with the length equal to the dead time value T_d.. Then, after reaching output value y_{21} at the time moment τ_{21i-1} (point 2) due to the effective plant input $U_1 = (v - M)K_s$ the output starts to decrease. After the time interval t_1 it reaches the reference value w (point 3). Even though at this moment the relay switches to the positive value $u = M$ the plant output continues to fall the time T_d longer and reaches the value y_{12} (point 4). The total length of the interval with negative relay output will be denoted as t^-. Under virtue of the positive relay output the plant output starts to rise and reaches the reference value after the time t_2 (point 5). The total duration of the positive relay output may be denoted as

$$t^+ = t_2 + T_d \tag{2}$$

As a result of the time delay, the plant output turnover time instants τ_{21i} are shifted with respect to the relay reversal moments t_{21i} by T_d. Similar time shift exists among time instants τ_{12i} and t_{12i}, i.e.

$$\tau_{21i} = t_{21i} + T_d \quad ; \quad \tau_{12i} = t_{12i} + T_d \tag{3}$$

For a single integrator it is possible to formulate relations

$$\begin{aligned} y_{21} - w &= U_2 T_d \; ; \; t_1 = (w - y_{21})/U_1 \\ y_{12} - w &= U_1 T_d \; ; \; t_2 = (w - y_{12})/U_2 \end{aligned} \tag{4}$$

Period of one cycle may be denoted as

$$P_u = t^+ + t^- = 2T_d + t_1 + t_2 = \frac{4T_d M^2}{M^2 - v^2} \tag{5}$$

For a known value of the relay amplitude M and a known ratio of the positive and negative relay output duration over one cycle

$$\varepsilon = \frac{t^+}{t^-} = \frac{t_2 + T_d}{t_1 + T_d} = -\frac{v - M}{v + M} \tag{6}$$

it is possible to express the identified disturbance as

$$v = u_0 + v_n \tag{7}$$

This may be composed of the known intentionally set offset at the relay output u_0 and an unknown external disturbance v_n that may be identified as

$$v = M\frac{1-\varepsilon}{1+\varepsilon} \tag{8}$$

From (5) it then follows

$$T_d = \frac{P_u}{4}\left[1 - \left(\frac{v}{M}\right)^2\right] = P_u \frac{\varepsilon}{(1+\varepsilon)^2} \tag{9}$$

The output mean value over one cycle period may be expressed as

$$y_s = \frac{1}{P_u}\left[w + \int_0^{T_d} U_2 t\,dt + \int_{T_d}^{2T_d+t_1} \left(y_{21} + U_1(t - T_d)\right)dt + \int_{2T_d+t_1}^{P_u} \left(y_{12} + U_2(t - 2T_d - t_1)\right)dt \right] \tag{10}$$

$$y_s = \frac{1}{P_u}\left[w + \int_0^{T_d} K_s(v+M)t\,dt + \int_{T_d}^{2T_d+t_1} \left(y_{21} - K_s(v-M)(t - T_d)\right)dt + \int_{2T_d+t_1}^{P_u} \left(y_{12} + K_s(v+M)(t - 2T_d - t_1)\right)dt \right] \tag{11}$$

Finally, one gets formula for the plant gain

$$K_s = \frac{(1+\varepsilon)^2}{\varepsilon P_u}\frac{(y_s - w)}{v} = \frac{(1+\varepsilon)^3}{\varepsilon(1-\varepsilon)P_u}\frac{(y_s - w)}{M} \tag{12a}$$

It is also possible to calculate the plant gain by using the area A limited by $y(t)$ around w over one period (5), when

$$K_s = \frac{(1+\varepsilon)^4}{\varepsilon(1+\varepsilon^2)} \frac{A}{MP_u^2} \tag{12b}$$

In difference to (12a), this may also be used in the symmetrical case with $v = 0$ and $y_s = w$. So, to get the model parameters (1) it is enough to calculate the mean plant output value over one cycle of relay switching (11), or the equivalent area A, the period of oscillation (5) and the ratio of time slots with positive and negative relay output (6). The approximation should remain valid also in the case of constant input disturbance $v = const$. This may be considered to be composed of the intentionally introduced disturbance u_0 and of the external disturbance v_n

$$v = u_0 + v_n \tag{13}$$

In this way it is possible to introduce an additional free parameter for tuning enabling to work in any working point with arbitrarily low relay module M.

After carrying out the above procedure at least for two different reference signal values w_1 and w_2 and by evaluating changes of the identified disturbance values v_1 and v_2 in dependence on the mean output values y_{s1} and y_{s2} it is then possible to approximate the dependence

$$v = f(y_s) \tag{14}$$

If it has a negligible slope with respect to changes in y_s, the system is sufficiently well approximated by the IPDT model.

2. REAL EXPERIMENT

The thermo-optical plant laboratory model (Fig.3) offers measurement of 8 process variables: controlled temperature, its filtered value, ambient temperature, controlled light intensity, its derivative and filtered value, the fan speed of rotation and current. The temperature and the light intensity control channels are interconnected by 3 manipulated voltage variables influencing the bulb (heat & light source), the light-diode (the light source) and the fan (the system cooling). Besides these, it is possible to adjust two parameters of the light intensity derivator. Within Matlab/Simulink or Scilab/Scicos schemes [10] the plant is represented as a single block and so limiting needs on costly and complicated software packages for real time control. The (supported) external converter cards are necessary just for sampling periods below 50ms. Currently, more than 40 such plants are used in labs of several EU universities.

Fig. 3 Thermo-optical plant

The thermal plant consists of a halogen bulb 12V DC/20W, of a plastic pipe wall, of its internal air column containing the temperature sensor PT100, and of a fan 12V DC/0,6W (can be used for producing disturbances, but also for control).

The optical channel has two outputs. The non filtered light intensity measured by a photodiode and the filtered one, where the signal is filtered by an analogue low pass filter with time constant at about 20s.

The non-filtered light channel represents a very fast process which can be approximated as memoryless plant. In an ideal case static feedforward control with inverse process gain should be sufficient for such process. However the filtered optical channel was used for the experiments, where the analogue first order filter is used to filter the non-filtered light channel output. We analyzed the system parameters in several working points. The input of the system is the bulb voltage which is limited to 5V.

The following table shows the system parameters in all working points. Relay magnitude ranges from 3 to 5V and the setpoint (light intensity) ranges from 10 to 35.

Table 1. Average system parameters

w	M	Ks	Td	v
35	5	0,581038	0,5505	-2,89034
30	5	0,564979	0,57954	-2,52964
20	5	0,536201	0,582476	-1,77778
10	5	0,475311	0,562213	-0,98358
30	4	0,57706	0,472195	-2,64252
20	4	0,522255	0,508156	-1,86067
10	4	0,468589	0,522159	-1,01576
30	3	0,602765	0,389834	-2,78204
20	3	0,56064	0,442128	-2,03024
10	3	0,536333	0,448577	-1,2376

In Fig. 4, the measured and the approximated system output in one working point is compared.

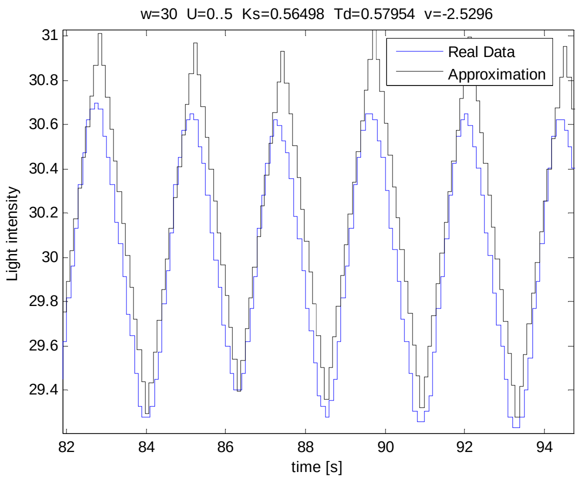

Fig. 4 Measurement and simulation comparison

3. PI CONTROLLER TUNING

PI controller was employed to control the plant to verify the identification results. To improve control performance the PI-controller structure from Fig. 5 was used.

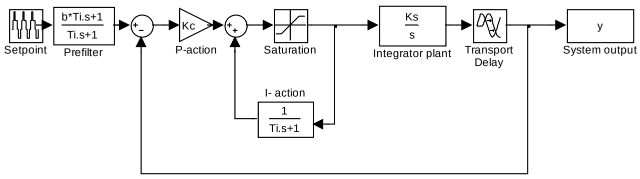

Fig. 5 PI1-controller

Performance portrait analysis was used to tune the controller. Upper left portrait shows the amount of an overshooting, the red area corresponds to controller tuning which yields overshooting up to 0.01%, the amount of overshooting grows to 5% in the blue area. The upper right portrait shows the control signal deviation from the defined shape. Lower portraits show the borders of the areas above.

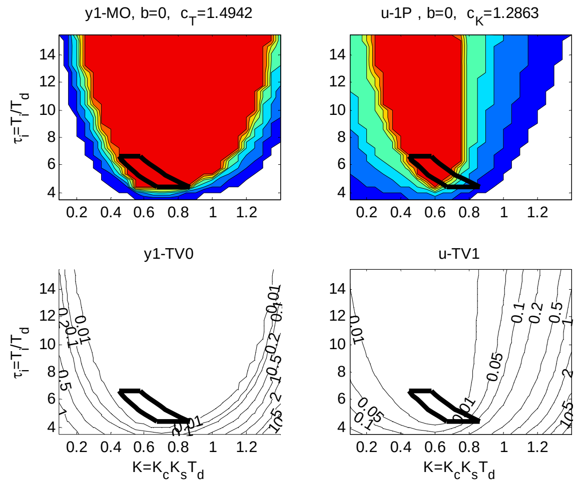

Fig. 6 Performance portrait

The following figures show the real experiment results for various setpoint changes. The controller was tuned to yield up to 0.1% overshooting.

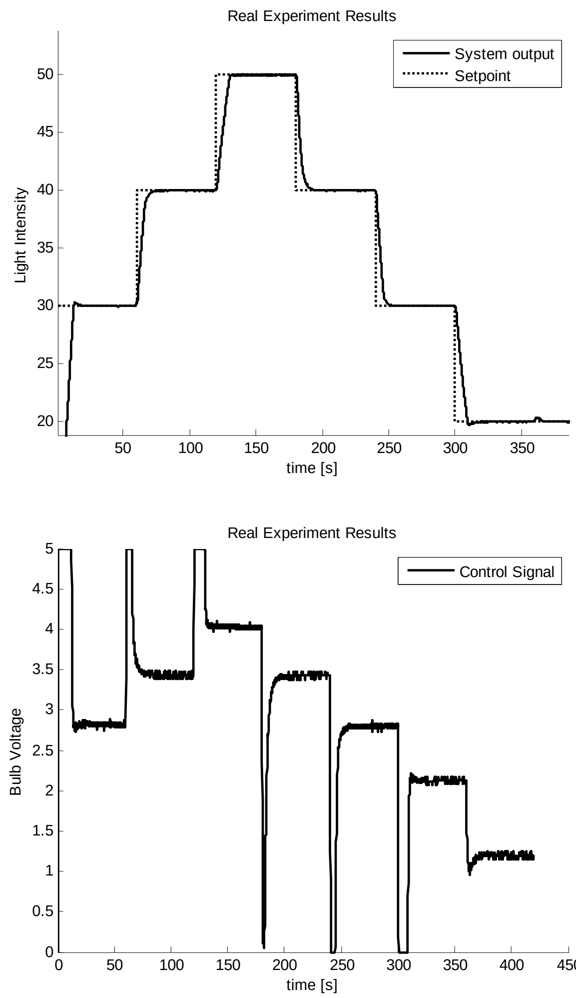

Fig.6 Control results

The control results in Fig. 6 show fast transients without overshooting except the last downward setpoitnt step, where a small overshoot occurs which results from the approximation imperfection. The control signal consists of two control phases: one can observe an interval at the saturation followed by the control signal's monotonic transition to the new steady state value.

4. CONCLUSION

New relay experiment identification method has been proposed for the IPDT plant. Stable optical plant with the first order dominant dynamics was used for illustrating and verifying the method by the real experiment. The method benefits from obtaining the load disturbance value without need of tuning a PI controller firstly. Sensitivity to the measurement noise that may lead to more complicated relay output than the considered period consisting of two pulses, can be at least partially eliminated by sampled-data relay control using longer sampling periods.

In applying the proposed method to controlling optical plant, the relay test yields results depending on the working point that obviously points out on nonlinear plant behaviour. In this paper, the nonlinear properties were treated by a robust controller tuning. One of the strong advantages of the proposed method, however, is its possible extension to identifying FOPDT model, or a nonlinear model with dominant first order dynamics + dead time. Nevertheless, due to the simple analytical formulas the proposed algorithm is easy to implement online.

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