APPLICATION OF A ROBUST TO DISTURBANCE RELAY FEEDBACK FOR IDENTIFICATION OF A GRAIN DRYER

Moisés Tavares da Silva*, Péricles Rezende Barros*

*Post-Graduate Program in Electrical Engineering - PPgEE - COPELE
Federal University of Campina Grande - Brazil
†Electrical Engineering Department
Federal University of Campina Grande - Brazil

Emails: moises.silva@ee.ufcg.edu.br, prbarros@dee.ufcg.edu.br

Abstract—The standard relay feedback method cannot provide a stable oscillation under large static disturbances or drift. In this paper, it is proposed a relay feedback structure to overcome this limitation. This structure is composed of a block to remove static disturbance or drift followed by a relay. The block consists of a simple high-pass filter followed by a relay plus an integrator. Describing function analysis shows that the proposed structure is similar to the standard relay. The proposed relay feedback structure is used to identify a first order plus time delay (FOPTD) model for a grain drying system in laboratory-scale.

Keywords—Relay feedback, Disturbance, Grain Dryer, Systems Identification.

1 Introduction

The relay feedback methods proposed by (Åström and Hägglund, 1984) have been applied to obtain the process ultimate information (phase angle equals to $-180^\circ$). In some cases, as processes under the effect of static disturbances or drift, the standard relay feedback method may fail. Many relay feedback methods have been proposed in order to overcome these cases.

Asymmetric relay oscillations occur in processes under static disturbance. This results in errors for the ultimate data estimation. To overcome this problem, (Hang et al., 1993) proposed the use of a biased relay feedback test under static input-side load disturbance. An output-biased relay is employed to restore symmetric output response of the process by (Shen et al., 1996). In (Sung and Lee, 2006b), it is proposed to set the time length of the lower part of the relay to half the time of the previous period. A change in the relay input reference value makes the output process to move to the new operating points.

Also to overcome the asymmetry problem of the relay experiment, in (Park et al., 1997) it is presented a relay correction by measuring the relay output variation and the gain at the frequency of the relay feedback to displace the input DC level. In contrast, a relay feedback method with a proportional-integral controller is proposed by (Friman and Waller, 1997), however this approach is sensitive to static disturbances. A similar approach proposed by (Sung and Lee, 2006a) also uses two channels — the proportional channel and the integral channel — in order to reject the static disturbance whose magnitude is larger than the magnitude of the relay. For the same purpose, a two-channel relay feedback method is used by (Sung et al., 2006).

In the presence of drift, a relay experiment may also present errors in the estimate of the ultimate information. A relay plus two filters is proposed by (Lee et al., 2011) to overcome the problems caused by slow drift. A low-pass filter is used to remove high frequency noise and a high-pass filter is used to remove low frequency drift. Large filter transients result in initial slow transient.

A grain dryer is used to control humidity and to treat stored seeds. Its operation is based on a flow of hot air that decreases the humidity of the seeds as a function of the temperature and the speed of the air flow (Araújo et al., 2005).

In this paper, a relay feedback structure made up of a block to remove static disturbance or drift followed by a relay is applied to a laboratory-scale grain drying thermal process. The block to remove disturbance consists of a simple high-pass filter followed by a relay plus an integrator. The integrator is used to cancel the dynamics of the high-pass filter. In order to separate the dynamics of the high-pass filter and integrator, a relay is used in between. The describing function analysis shows that the proposed structure does not change the oscillation characteristics of the relay feedback system.

The aim of the proposed relay feedback structure is not to estimate the ultimate frequency, but to obtain a limit cycle insensitive to disturbances. This frequency information obtained from the oscillation is used to estimate a FOPTD model of the grain drying system.

This paper is organized as follows: in Section 2, the proposed relay feedback structure is discussed; in Section 3 is presented a describing function analysis of the proposed relay feedback structure; in Section 4, the experimental setup of grain drying system is described; the FOPTD model identification technique used is presented in Section 5; experimental results are presented in Section 6; in Section 7 conclusions are discussed.
2 Proposed Relay Feedback Structure

In this Section, the problems presented by the standard relay under disturbance are described. In order to overcome these problems, a relay feedback structure is proposed.

2.1 Standard relay under disturbance

Consider the schematic diagram for the standard relay feedback method shown in Figure 1. The signals \( u \) and \( y \) are the process input and output, respectively. \( d \) represents a static disturbance or drift and \( r \) the reference signal.

![Figure 1: Relay feedback system.](image)

Under certain conditions the relay feedback test results in a sustained oscillation at the process output, with the oscillation period near the process ultimate period.

The effect of a disturbance applied to the process has been demonstrated by the following case study.

Consider a second order plus time delay process

\[
G(s) = \frac{1}{(s+1)^2}e^{-s}. \tag{1}
\]

This process is simulated with a standard relay, the amplitude of which is \( h = 1 \). The sampling time used is 0.01s and a static disturbance with \( d = 0.9 \) is applied at the process input at time \( t = 20s \). At time \( t = 40s \), a static disturbance with \( d = 2 \) is applied at the process input. The oscillation period of the process is \( T_u = 4.81s \). In Figure 2, the process input and output signals are presented.

Before the introduction of static disturbance into the system, the oscillation period is \( T_u = 4.78s \). From time \( t = 20s \), when the static disturbance is introduced into the system, the oscillation becomes asymmetric, with period \( T_u = 6.51s \). From time \( t = 40s \), the standard relay test will fail to produce a stable oscillation.

2.2 Proposed relay structure under disturbance

Consider now the relay experiment structure shown in Figure 3. This structure is composed of two blocks, the first one is to remove static disturbance or drift. The second block is a standard relay \( R_2 \). The block to remove disturbance consists of a high-pass filter, \( F_1(s) \), followed by a relay \( R_1 \) and a low-pass filter, \( F_2(s) \).

The high-pass filter \( F_1(s) \) is given by

\[
F_1(s) = 1 - e^{-sT_f}. \tag{2}
\]

In the present paper, the filter time constant \( \tau_f \) is chosen as the sampling time of the process. Note that \( F_1(s) \) is an approximate derivative, \( s\tau_f \).

The low-pass filter is chosen as a simple integrator, i.e., \( F_2(s) = 1/s \). The integrator is used to cancel the high-pass filter dynamics. In order to separate the dynamics of the high-pass filter and the low-pass filter, the relay \( R_1 \) is introduced.

The high-pass filter removes the static disturbance or drift. The relay \( R_2 \) is used as the standard relay to generate a stable oscillation at the process output.

The process represented by Eq. (1) is now simulated for the proposed relay feedback structure with filter time constant \( \tau_f \) equals to sampling time (0.01s). The magnitudes of the two relays are the same, \( h = 1 \). Again, static disturbances of \( d = 0.9 \) and \( d = 2 \) are applied at the process input at time \( t = 20s \) and \( t = 40s \), respectively. In Figure 4, the process input and output signals are showed. As can be seen, the proposed relay feedback structure provides a symmetrical relay output under static disturbance. In both cases, with and without static disturbance introduced into the system, the oscillation period is \( T_u = 5.12s \).

For large static disturbance, the proposed relay feedback structure provides a symmetrical oscillation. Again, with and without static disturbance introduced into the system, the oscillation period is \( T_u = 5.12s \).

Remarks

1. In (Sung and Lee, 2006a), an integral gain must be updated by iterative procedure to
ensure consistent performances in rejecting large static disturbances. In the proposed structure, no need for an iterative procedure.

2. In order to ensure rejection of a large static disturbance, in (Sung et al., 2006) it is necessary to update parameters and mode of operation of the proposed structure during the relay feedback test. However, for the proposed structure, it is necessary to define previously only the filter time constant.

3. In (Lee et al., 2011), the design of two filters is needed. The proposed block to remove disturbance is similar to this approach. However, in the proposed structure it is necessary to define only the filter time constant of the high-pass filter. This is favorable from a practical point of view.

4. For noisy environments, one can use a hysteresis to avoid chattering of the output of relay near the crossing point.

3 Describing Function Analysis

Methods for determining the describing function of a system containing a single nonlinear element, as Figure 1, are well-known (Åström and Hagglund, 1984).

Assuming a sine wave is present at the input of the nonlinear element and its output contains no zero frequency and no subharmonic terms, the describing function is obtained by computing the ratio of the Fourier coefficient of the first harmonic at the output signal to amplitude of input signal (Khalil, 1996).

The describing function for the ideal relay is given by

\[ N(A) = \frac{4h}{\pi A}. \]  

where \( h \) is the amplitude of the relay and \( A \) is the amplitude of the input signal.

Lemma 1 Consider the proposed relay feedback structure shown in Figure 3. The transfer function of \( F_1(s) \) is given by Eq. (2), and \( F_2(s) \) is an integrator. Both relays have the same amplitude \( h \). Assume the phase angle of the filter \( F_1(s) \) is \( \theta_1 \) at the frequency \( \omega \). The describing function for the proposed structure is given by

\[ N(A, \omega) = \frac{4h}{\pi A} e^{j(\theta_1(\omega) - \pi/2)}. \]  

Proof: Assume symmetric and odd nonlinearities for both relays. Also, the relays have the same amplitude \( h \). Consider the input signal of the first filter \( (F_1(s)) \) as

\[ u(t) = A \sin(\omega t). \]  

The output signal from this filter is given by

\[ m(t) = A |F_1(j\omega)| \sin(\omega t + \theta_1(\omega)), \]  

where

\[ F_1(j\omega) = |F_1(j\omega)| \exp(\theta_1(\omega)) = |F_1(j\omega)| e^{j\theta_1(\omega)}. \]  

The frequency response for \( F_1(s) \), Eq. (2), is given by

\[ |F_1(j\omega)| = \left[ (1 - \cos \omega \tau f)^2 + (\sin \omega \tau f)^2 \right]^{1/2}. \]

\[ \theta_1(\omega) = \tan^{-1}\left( \frac{\sin \omega \tau f}{1 - \cos \omega \tau f} \right). \]
For the $R_1$ relay, the first harmonic of the Fourier series is

$$n(t) = \frac{4h}{\pi} \sin(\omega t + \theta_1(\omega)). \quad (7)$$

Under the assumptions of symmetric and odd nonlinearities, the analysis is simplified. The describing function for the $R_1$ relay is given by

$$N_1(A, \omega) = \frac{4h}{\pi A |F_1(j\omega)|}. \quad (8)$$

The output for the second filter ($F_2(s)$) is given by

$$w(t) = \frac{4h|F_2(j\omega)|}{\pi} \sin(\omega t + \theta_1(\omega) + \theta_2(\omega)), \quad (9)$$

where

$$F_2(j\omega) = |F_2(j\omega)| e^{j\theta_2(\omega)}.$$  

The output signal of $R_2$ relay, $z(t)$, is given by

$$z(t) = \frac{4h}{\pi} \sin(\omega t + \theta_1(\omega) + \theta_2(\omega)). \quad (10)$$

Thus, the describing function for the $R_2$ relay is

$$N_2(A, \omega) = \frac{1}{|F_2(j\omega)|}. \quad (11)$$

Therefore, the describing function of the proposed relay feedback structure is

$$N(A, \omega) = F_1 \times N_1 \times F_2 \times N_2 = \frac{4h}{\pi A} e^{j(\theta_1(\omega) + \theta_2(\omega))}. \quad (12)$$

where $\theta_2(\omega)$ is the integrator phase angle $-\pi/2$. Therefore,

$$N(A, \omega) = \frac{4h}{\pi A} e^{j(\theta_1(\omega) - \pi/2)}. \quad (13)$$

For low frequencies, the filter $F_1(s)$ has a phase angle of approximately $+\pi/2$. This can be verified in the Bode diagram (Figure 5) for $F_1(s)$, Eq. (2), and a pure derivative $s\tau_f$. Therefore, the describing function analysis shows that the proposed structure is similar to the standard relay.

4 Grain Drying System

The grain drying system is represented in Figure 6. The grains are deposited on a metal screen, as shown in the Figure 6. The air, at ambient temperature, is forced into the main chamber by the fan $V_1$, where it is heated by the electric resistance $R$. The fan $V_2$ forces the air inlet at ambient temperature into the main chamber. For control studies, the fan $V_2$ air is used as system disturbance input.

The temperature measurement is performed by the sensor $S_1$. The sensor response time is short when compared to the response time of the system. As result, its influence can be neglected.

The system output, $PV$ (Process Variable), is the temperature on the metal screen measured by the sensor $LM35$ ($S_1$). The temperature data is obtained by an analog module that makes the data available to the PLC (Programmable Logic Controller) $eZAP901$ of the $HI$ Tecnologia. The control signal ($MV$ - Manipulate Variable) is obtained from the $PWM$ actuator in the grain drying system. The computational interface used to perform the experiments was the $MATLAB$ software. This interface communicates with the PLC through the OLE for Process Control standard (OPC).

More details of the experimental setup can be found in (Araújo et al., 2005).

5 FOPTD Model Identification

A FOPTD model can be obtained by the process steady state gain in addition to frequency limit cycle information. Once the proposed relay feedback structure removes a static disturbance and ensures
symmetric of output process, a step change in the input process can be applied without disturbing the relay feedback operation. This step change in the process input provides the process steady state gain.

The data obtained from the proposed relay feedback structure is used to identify a FOPTD model of the grain drying system. The identification technique based on the relay experiment proposed by (Åström and Hägglund, 2006) is applied.

Consider a FOPTD model with transfer function given by $G(s)$, Eq. (14). At frequency $\omega$, $G(j\omega)$ and $\phi(\omega)$ are the gain and the phase of the system, respectively.

$$G(s) = \frac{K}{Ts + 1} e^{-sL}. \quad (14)$$

The steady-state gain ($G(0)$) can be obtained by integrating system input-output response. $G(j\omega)$ is estimated by a relay feedback test. The other parameters for the FOPTD model can be calculated using the following equations

$$T = \frac{1}{\omega} \left( \frac{|G(j\omega)|}{G(0)} \right)^{-2} - 1 \quad (15)$$

$$L = \frac{1}{\omega} (\pi - \arctan \left( \frac{|G(j\omega)|}{G(0)} \right)^{-2} - 1) \quad (16)$$

$$K = G(0). \quad (17)$$

6 Experimental Results

Initially, in order to obtain the steady-state, the PWM set to 30% was applied at the process input. The final value in steady-state was approximately 48.5°C. During the experiments, only the fan V1 was used. The amplitude of the R1 relay was adjusted to $h = \pm 1$. While, the R2 relay was adjusted to apply oscillations around the reference MV with an amplitude of $h = 5$. The hysteresis was adjusted to $\pm 0.1$. The filter time constant ($\tau_f$) is equal to the sampling time, which is 1s.

In order to obtain the process steady state gain, a step change of $d = 5$ was applied at the process input at time $t = 90s$. These conditions were applied to the proposed relay feedback structure and the standard relay experiment. The process input and output signals obtained by the proposed relay experiment are shown in Figure 7. The signals obtained by the standard relay experiment are shown in Figure 8.

The FOPTD model estimated using Eqs. (15)-(17) and the input-output data obtained by the proposed relay feedback structure is

$$G_{pro}(s) = \frac{0.3712}{5.237s + 1} e^{-3.47s}. \quad (18)$$

For the standard relay experiment, the FOPTD model estimated is

$$G_{sr}(s) = \frac{0.2344}{3.747s + 1} e^{-4.26s}. \quad (19)$$

In order to validate the FOPTD models obtained, steps were applied at the process input. The accuracy of the estimated model is evaluated using the normalized root mean square error, Eq. (20). The value of this cost function vary between $-\infty$ (bad fit) to 1 (perfect fit).

$$\epsilon = \left(1 - \frac{||y(kTs) - \hat{y}(kTs)||}{||y(kTs) - mean(y(kTs))||}\right). \quad (20)$$

where $kTs$ is the sampling instants, $Ts$ is the sampling time, $y(kTs)$ is the actual output of the process, $\hat{y}(kTs)$ is the estimated output and $mean(y(kTs))$ the process output mean.

The step responses for the experimental setup are shown in Figure 9. For the model obtained us-
ing the data of the proposed relay feedback structure the cost function value is $\epsilon = 0.7243$. While, for the model obtained by the standard relay experiment $\epsilon = 0.08314$.

![Figure 9: Process output (Solid line), model output of $G_{pr}(s)$ (Dashed line), model output of $G_{sr}(s)$ (Dash-dotted line) signals of the validation test.](image)

7 Conclusion

A relay feedback structure was used to obtain a stable oscillation under disturbance and identify a FOPTD model of the laboratory-scale grain drying system. Since the proposed relay feedback structure removes static disturbance and ensures the process output symmetric, a step change in the process input can be applied without disturbing the relay feedback operation. Experimental results show that the FOPTD model obtained for the grain drying system using the proposed relay feedback structure data is accurate.

ACKNOWLEDGMENT

This work was supported in part by the CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior).

References


