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A performant PID autotuner based on a short relay test ⋆

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Abstract: Industrial applications encompass a wide range of fields, including chemical plants, biomedical engineering, vibration control, and mechanical systems, among others. Frequently, controller tuning is performed using a process model as a basis. Determining such a model can be a time-consuming and challenging task, requiring proper identification. Nonlinear processes often have a limited number of relevant operating points. Autotuning methods that collect pertinent process information at specific operating points and determine controller parameters automatically streamline the controller design process by eliminating the need for process modelling. This paper presents a novel relay based autotuning methodology for Proportional Integral Derivative (PID) controllers highly suitable for Industry 5.0 applications that is easily implemented. The methodology is successfully validated on two numerical examples consisting of a highly oscillatory process and a process with large time delay. Additionally, two experimental validations are presented for a mass-spring-damper system and a 2-tank process.

Keywords: PID control, industrial control, relay autotuner

1. INTRODUCTION

There is no doubt that the PID controller occupies a key role in industrial control. Rising customer expectations for superior product quality, stricter safety standards, and heightened worldwide competitiveness lead to processes frequently functioning under conditions exhibiting inherent nonlinearities. Obtaining an accurate process model for big industrial plants with complex loop interactions can be a challenging task. Therefore, it is justified to use autotuning methods to determine the parameters of the controller, eliminating the need of a process model (Hornsey (2012); Wang (2001); Zhuang and Atherton (1993); Muresan, Cristina I. and Birs, Isabela Roxana and Ionescu, Clara-Mihaela and Dulf, Eva H. and De Keyser, Robain (2022)).

Direct autotuning methods use simple process tests (step, relay or sine) to find relevant information about the process which is further used to compute the controller parameters. The Ziegler-Nichols (ZN) method is the most commonly used autotuning methodology. It is a simple approach that relies purely on the critical gain and critical frequency of the process to determine the integer-order PID parameters (Ziegler and Nichols (1942)]). Although this approach is recognised for its remarkable ability to reject disturbances, it typically lacks in accurately tracking references (Hornsey (2012)). Other popular autotuning methods include the Åström-Hägglund method as initially proposed in (Aström and Hägglund (2004)) which enhances the original ZN approach by incorporating a stability-oriented tuning need through the imposition of limits on phase or amplitude margins.

Another relay based methodology, known as the KC autotuner, has been developed by De Keyser et al. (2019) with various experimental validations proving the efficacy of the method in (De Keyser, Robain and Birs, Isabela Roxana and Muresan, Cristina I. (2020); De Keyser, Robain and Muresan, Cristina I (2019)) and (Shiquan et al. (2018)). A 'forbidden region' may be generated on the Nyquist plane in accordance with the user-defined requirement. One can subsequently determine the system's dynamic near the operating point by conducting a basic sine test. By strategically developing a PID controller, it is possible to make the frequency response of the loop tangent to the 'forbidden region' in order to satisfy the specified criteria.

This paper presents a novel relay based uncomplicated design methodology which is built on a strong theoretical foundation, with immediate practical applicability regarding PID controller autotuning. The main idea focuses on a short relay test, followed by Fourier Transform computations of the input, output signals and their respective

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derivatives. The controller parameters can be computed using any desired autotuning method such as ZN, KC, etc. after the relevant process information is extracted. The method is validated on two numerical examples and two experimental platforms. The obtained results are provided in comparison to the popular ZN autotuner in order to validate the proposed approach.

The paper is structured as follows: Section 2 presents the basic principles of relay autotuners with an emphasis on ZN and KC strategies; Section 3 presents the novel methodology from a practitioner's perspective providing step by step instructions; with numerical validations presented in Section 4 and experimental validations in Section 5. Finally, Section 6 concludes the paper.

2. AUTO-TUNING PRINCIPLES

Relay auto-tuning is based on the simple idea of investigating process dynamics by the oscillation obtained when the PID controller is replaced by a relay function in a closed loop system structure, offering several advantages. Firstly, it eliminates the risk of loop instability that can occur with the Ziegler-Nichols cycling method. Secondly, it requires minimal prior knowledge of the plant. Lastly, by selecting the appropriate relay parameters, the loop output can be maintained close to the set-point during the test (Hansson et al. (2021); Liu et al. (2023)). Fig. 1 presents the block diagram of the relay based autotuning principle. $P(s)$ denotes the physical process, whose transfer function is unknown.

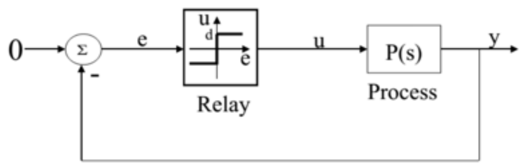

Fig. 1. Schematic of the relay auto-tuning principle

The relay test is performed as shown in Fig. 1 to determine the parameters of the PID controller

$$C(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{1}$$

where K_p is the proportional gain, T_i denotes the integral time, while T_d is the derivative time constant.

The loop frequency response ($s = j\omega$) is given by

$$L(j\omega) = C(j\omega)P(j\omega). \tag{2}$$

2.1 The ZN autotuner

Let us consider the frequency $\bar{\omega}$ which is the critical frequency of the process.

Given the value $P \triangleq P(j\bar{\omega})$, the parameters of the PID controller from (1) are obtained such as the loop frequency response from (2) goes through a specific point in the Nyquist plane at frequency $\bar{\omega}$.

The intersection point previously mentioned is specified by the complex number L, defined as

$$L \triangleq L(j\bar{\omega}). \tag{3}$$

For the ZN autotuner, we have

$$L = -0.60 - j\ 0.28. \tag{4}$$

The solution is obtained by equating the controller's (1) frequency domain transfer function with the ratio between L and P

$$C(j\bar{\omega}) = K_p\left(1 + \frac{1}{j\ T_i\bar{\omega}} + j\ T_d\bar{\omega}\right) = \frac{L}{P}. \tag{5}$$

The methodology uses only the complex number P to compute the controller's parameters. Note that

$$T_i = 4T_d \tag{6}$$

is a design specification of the ZN methodology.

2.2 The KC autotuner

The KC autotuner is based on the Nyquist representation from Fig. 2. A forbidden region circle is defined (green line) having the centre -1.25 and radius 0.75. The goal is to reduce the yellow angle to zero by moving the red point along the green circle; i.e. to shape the loop frequency response to touch the circle.

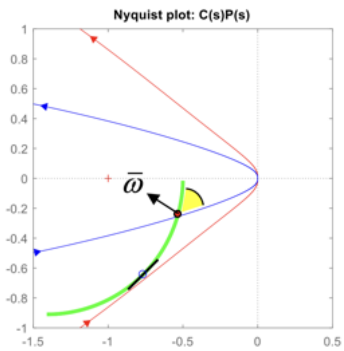

Fig. 2. KC autotuner principle: forbidden region circle (green), loop frequency response of the ZN result going through the red point -0.6-0.28j (blue), loop frequency response of the KC result (red)

The three parameters of the PID controller are determined by selecting a point L on the circle, as defined in (3) and solving (5). The complex number dL can be computed as

$$dL = C\ dP + P\ dC, \tag{7}$$

with $C = \frac{L}{P}$ and $dC \triangleq j\ K_p\left(\frac{1}{T_i\bar{\omega}^2} + T_d\right)$. P and dP can be computed based on the relevant process data acquired from the relay test.

The slope S of the loop frequency response at point $\bar{\omega}$ is given as

$$S = \arctan\frac{imag(dL)}{real(dL)}. \tag{8}$$

The solution of the KC design procedure is to find the point L on the circle for which S is as close as possible to the circle slope in that point.

3. PROPOSED SHORT RELAY TEST

In order to obtain P in (5) and dP in (7) we propose the following procedure:

(1) Start a relay test with input $u(t)$ and stop it at time T, where T is the settling time of the process. Keep measuring until $t = 2T$.
(2) Estimate the relay oscillation period $\bar{\omega}$ from $u(t)$.
(3) Compute the following complex numbers: $U(j\bar{\omega})$, $dU(j\bar{\omega})$, $Y(j\bar{\omega})$ and $dY(j\bar{\omega})$. $\bar{\omega}$ is a given radial frequency, $U(j\omega)$ is the Fourier Transform of an input signal $u(t)$, while $dU(j\bar{\omega})$ is the slope (derivative) of $U(j\bar{\omega})$. $Y(j\bar{\omega})$ and $dY(j\bar{\omega})$ are related to the output signal.
(4) Use the two complex numbers $P = \frac{Y}{U}$ and $dP = \frac{dY - PdU}{U}$ to tune a PID controller using any autotuning method.

Relay tests present in autotuning procedures start after the process reaches steady state ($t > T$), while the test from Step 1 is performed in the first T seconds. The advantage is that the relay test is much shorter, since $u(t) = 0$ at $t = T$. The signals $u(t)$ and $y(t)$ are deviation values with respect to the operating point, returning to 0 after the experiment is performed. In the absence of disturbance signals, P and dP from Step 4 are perfect estimations of the frequency response and its slope.

4. NUMERICAL VALIDATIONS

4.1 Example 1: Very oscillatory process

Consider the transfer function of a very oscillatory process described by

$$P(s) = \frac{20}{(1 + 0.2s)^3(s^2 + 1.2s + 36)} \tag{9}$$

with settling time $T = 6$ seconds.

Performing the relay test described in Step 1, gives the response from Fig. 3. As indicated in Step 1, the relay test runs for the first 6 seconds, while for the next 6 seconds the input is zero. The radial frequency is estimated as $\bar{\omega} = 5.3$ based on the output signal.

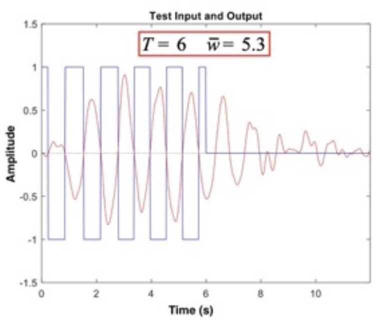

Fig. 3. Relay test for Example 1: input (blue) and output(red)

The Nyquist response of the process from (9) is shown in Fig. 4. The estimated point at frequency $\bar{\omega}$ is shown with red. Note that P(s) is used only to verify if the estimated point is on to the Nyquist plot and this transfer function is unknown in practice.

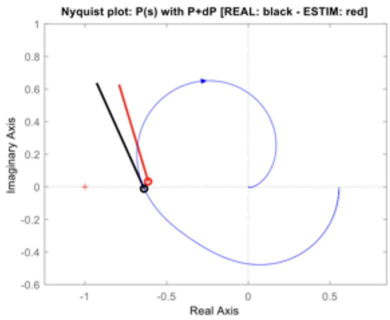

Fig. 4. Nyquist plot of (9) and estimated point for Example 1

The autotuning methodology from Section 2 for both ZN and KC controllers tuned in Step 4 gives:

- KC controller: $K_p = 0.81, T_i = 0.26, T_d = 0.15$,
- ZN controller: $K_p = 0.95, T_i = 0.63, T_d = 0.16$.

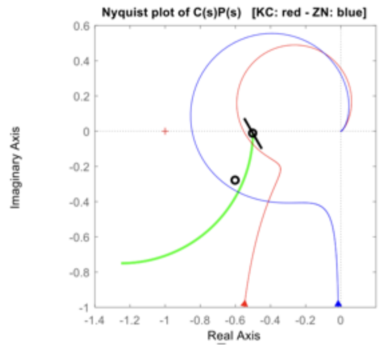

Fig. 5. Nyquist plot of the loop frequency responses for Example 1

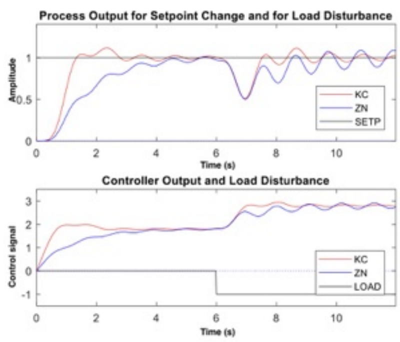

Fig. 6. Step responses of the process with KC and ZN autotuners for Example 1

The loop frequency responses with both controllers are shown in Fig. 5, while the two controllers are successfully validated in Fig. 6. As can be seen, the KC autotuner obtains a settling time of 1 second, better than the ZN controller that stabilizes in 5 seconds. A load disturbance is introduced at $t = 6$ seconds, both controllers successfully rejecting it. The KC methodology outperforms ZN also for the disturbance rejection scenario.

4.2 Example 2: Process with large time delay

The second numerical example consists of a process with a large time delay, described by

$$P(s) = \frac{1.2}{(10s+1)(5s+1)(2s+1)} e^{-10s}. \quad (10)$$

Performing the relay test for the duration of the process' settling time $T = 70$ seconds gives the results presented in Fig. 7. The estimated radial frequency from Step 2 is $\bar{\omega} = 0.137$.

Fig. 7. Relay test for Example 2: input (blue) and output(red)

The estimated point from Step 4 is validated on the process' Nyquist response in Fig. 8.

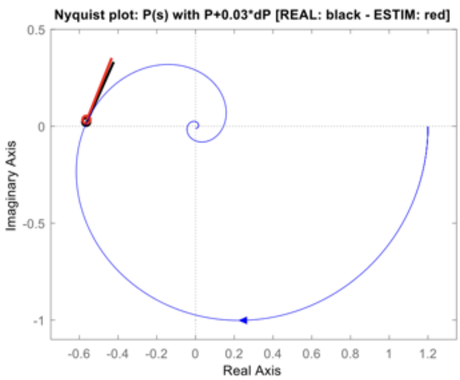

Fig. 8. Nyquist plot of (10) and estimated point for Example 2

The ZN and KC controllers are obtained as

- KC controller: $K_p = 0.89, T_i = 19.0, T_d = 4.75$,
- ZN controller: $K_p = 1.04, T_i = 24.4, T_d = 6.11$.

The two loop responses of the open loop systems with the ZN and KC autotuners are shown in Fig. 9. Note the angle between the KC response and the circle being close to 0^o.

A unit step reference signal is given in Fig. 10, followed by a -1 load disturbance introduced at time $t = 100$ seconds. Both controllers obtain good performance, with similar settling times and disturbance rejection capabilities.

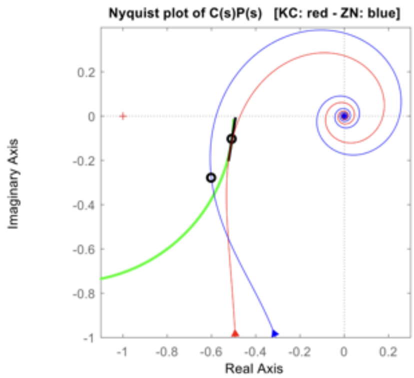

Fig. 9. Nyquist plot of the loop frequency responses for Example 2

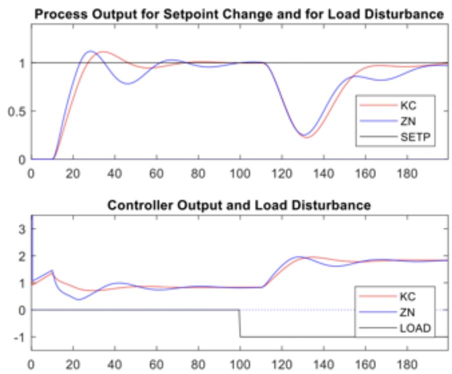

Fig. 10. Step responses of the process with KC and ZN autotuners for Example 2

5. EXPERIMENTAL VALIDATION

5.1 Example 3: Mass-Spring-Damper

An experimental setup consisting of a mass spring damper (MSD) is considered as the first experimental case study. The platform is shown in Fig. 11. The MSD pilot plant is equipped with a single input, denoted as u(t) and two outputs, y1(t) and y2(t). The motor's propelling force, denoted as the actuator, is directly proportional to the input voltage u(t). It exerts a direct influence on M1. Collocated control refers to the situation in which the actuator and sensor share the same mass in order to manipulate the position of M1. Non-collocated control refers to the situation in which the actuator and sensor have distinct masses and we wish to manipulate the position of M2. The present illustration centres on the regulation of M1. Disconnecting the first and third springs transforms this configuration into an integrating system.

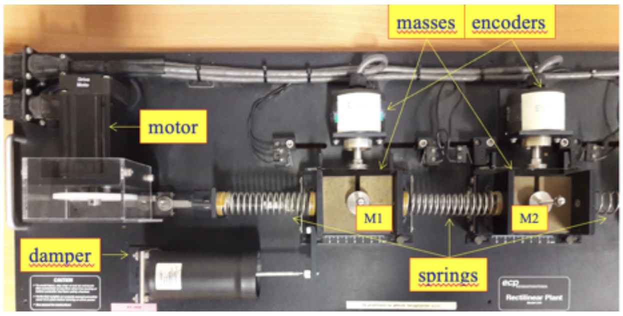

Fig. 11. MSD system used for Example 3

The process transfer function is known and will be used only for validation purposes regarding the Nyquist response. The tuning is completely independent to the process' model

$$P(s) = \frac{1676(s^2 + 0.74s + 74)}{s(s + 10)(s + 3.32)(s^2 + 2.28s + 121)}. \quad (11)$$

Two consecutive relay experiments are used for the duration of the settling time $T = 5$ seconds to improve the signal over noise ratio, as shown in Fig. 12. These are realized using the closed loop system with the controller $C(s) = K_p = 0.1$ because of the integrating nature of the process.

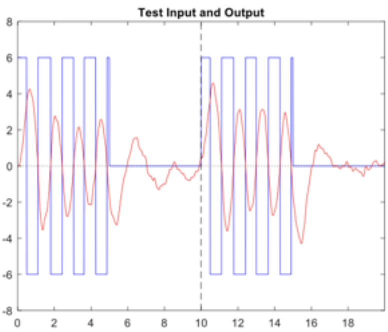

Fig. 12. Closed loop relay test for Example 3: input (blue) and output(red)

The estimated point from Step 4 for the radial frequency $\bar{\omega} = 5.2$ is overlayed on the process' Nyquist response in Fig. 13.

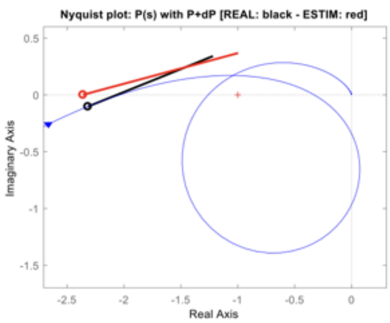

Fig. 13. Nyquist plot of (11) and estimated point for Example 3

The ZN and KC controllers are obtained using the auto-tuning methodology as

- KC controller: $K_p = 0.35, T_i = 0.61, T_d = 0.2$,
- ZN controller: $K_p = 0.25, T_i = 0.6, T_d = 0.15$.

Fig. 14 shows the loop frequency response with the two controllers.

Experimental validations of the closed loop systems with both controllers are performed in Fig. 15. The KC auto-tuner gives an improved settling time of 1 second when compared to the ZN controller which obtains 3 seconds. In addition, the overshoot is larger with the ZN controller. Furthermore, the KC methodology rejects the load disturbance much faster.

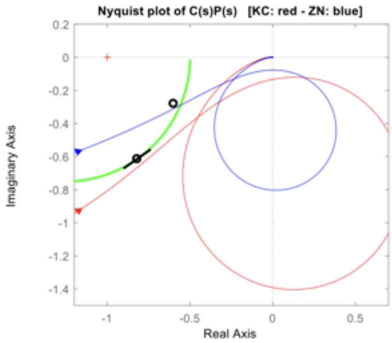

Fig. 14. Nyquist plot of the loop frequency responses for Example 3

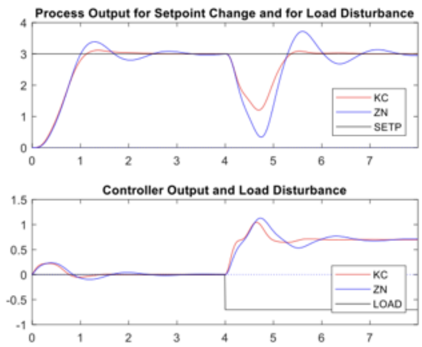

Fig. 15. Experimental responses of the process with KC and ZN autotuners for Example 3

5.2 Example 4: Quanser 2-Tanks

The last example features experimental validations on the Quanser 2-Tanks process from Fig. 16. The objective is to control the height h_2 (cm) using the manipulated variable V_i (V). Due to the integrating nature of the process, a closed loop relay test is performed with the controller $C(s) = K_p = 0.2$. Two consecutive relay experiments are used for the duration of the settling time $T = 250$ seconds to improve the signal over noise ratio, as shown in Fig. 17.

The radial frequency from Step 2 is computed as $\bar{\omega} = 0.039$, while the parameters of the two controllers are

- KC controller: $K_p = 0.22, T_i = 141, T_d = 17.6$,
- ZN controller: $K_p = 0.23, T_i = 77.1, T_d = 19.3$.

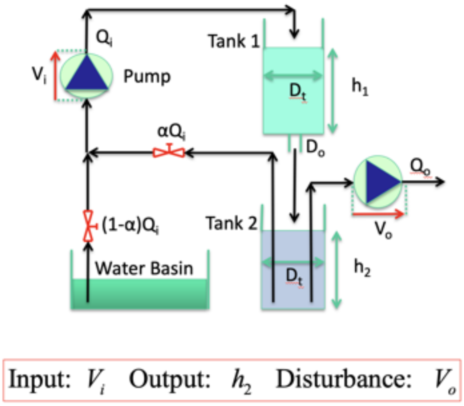

Fig. 16. Quanser 2-Tanks system used for Example 4

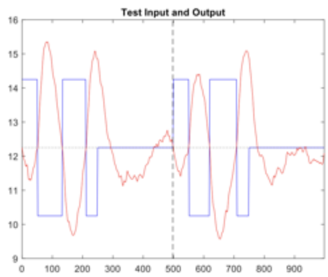

Fig. 17. Closed loop relay test for Example 4: input (blue) and output(red)

Experimental validations are performed in Fig. 18. At moment $t = 1500$ seconds, the load disturbance V_o from Fig. 16 is employed. The KC controller outperforms the ZN autotuners in both scenarios, based on overshoot and settling time.

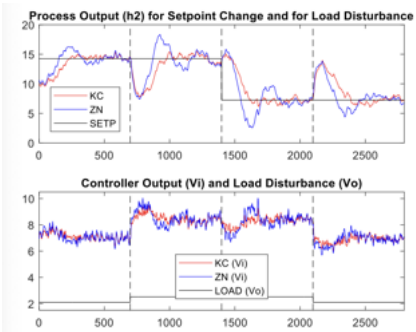

Fig. 18. Experimental responses of the process with KC and ZN autotuners for Example 4

6. CONCLUSION

In industrial processes, a model is usually not available. The paper proposes a short relay test based on transient data in order to obtain an estimate of a specific frequency domain point and the slope in that point. This allows the tuning of a PID controller using any available method. The proposed methodology is validated using two autotuners: ZN and KC which are successfully validated on two numerical examples and two experimental setups. The KC approach proves to be a better choice for reference tracking and disturbance rejection when compared to a controller tuned using the ZN method.

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