

Model-free PID Controller Autotuning Directly Applicable to Real Control Loops

Stanislav Vrána*, Bohumil Šulc**

*Czech Technical University in Prague, Faculty of mechanical Engineering
Department of Instrumentation & Control Engineering, Prague, Czech Republic
(Tel: +420 2 2435 2651*, +420 2 2435 2531**;
e-mail: stanislav.vrana@fs.cvut.cz*, bohumil.sulc@fs.cvut.cz**)*

Abstract: Many PID controller tuning methods have been presented since Ziegler and Nichols published their method in 1942, but none of those methods were used widely. The Ziegler and Nichols method has several advantages over newer methods: it is easy to conduct, the relations for controller parameter computation are simple, the method relies on experiment, and it does not require any model. Newer tuning methods are usually model-based, but the model-free methods are preferred in common industrial practice. This paper presents a model-free tuning method that respects the “restrictions” given by the easy usage of the Ziegler and Nichols method. The method is model-free, and new controller parameter computation is based on evaluation of control quality indicators. The evaluation is done without disconnection of the controller and with no other control restrictions during control.

Keywords: PID, control, selftuning control, harmonic, excitation, model-free

1. INTRODUCTION

Many tuning methods have been developed since 1942, when Ziegler and Nichols presented their method that is still used in a significant number of tuning procedures conducted everyday. The Ziegler and Nichols method has several advantages. First, it is based on experimentations done on site, i.e. with a real control circuit whose operation reflects all nonlinearities influencing control quality. It is difficult to be done with the tuning methods especially based on models of the controlled plant. However, it is known that use of the controller parameter settings obtained by means of the Ziegler and Nichols method leads to a stable, but from the viewpoint of settling, sometimes unsatisfactory control because it oscillates too much and reaches the desired setpoint value slowly.

To obtain better control results, some more modern tuning methods have been proposed, usually they represent only slight modifications to the Ziegler and Nichols method. For

example, some of them use only different coefficients in relations for controller parameter computation, others have these coefficients parameterized. The relay method (Åström and Hägglund, 1984) is also an extension of Ziegler and Nichols method that allows undamped oscillations in the control loop without setting the controller at the stability margin.

The popularity of the Ziegler and Nichols procedures motivated us to develop a new tuning procedure, whose principle is described in next paragraph. The new procedure retains the advantages of the Ziegler and Nichols method and contributes some new ones, e.g. the tuning procedure done in a closed loop during control, possibility for the controller operator to influence the control quality, and easy addition into the existing control loops.

2. PRINCIPLE OF THE PROPOSED TUNING METHOD

The method is based on added harmonic excitation into the loop that allows control quality indicator evaluation without disconnecting the controller or any other restriction of control.

Figure 1 shows the block scheme of the closed control loop with the added tuning mechanism. The mechanism adds a harmonic excitation b to the control error e . This summation produces a control error with added harmonic excitation e_b . Controller quality indicators are evaluated from the course of the control error e and the control error with added harmonic excitation e_b .

The control quality indicators are values that are connected with the Nyquist plot in a linear case, but they are measurable experimentally also in a non-linear case. Typical examples of

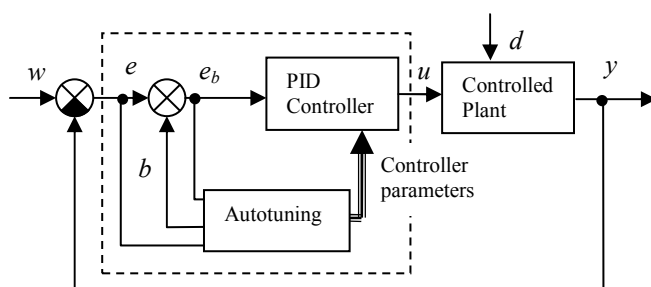


Fig. 1. Scheme of a control circuit with an added autotuning mechanism

Initial situation, the amplitudes of both signals differ, the Phase Margin γ is unevaluable.

The frequency of excitation signal changed to ω_2 , controller parameter remains the same. It is possible evaluate the Phase Margin γ_2 but it is not equal to its desired value.

The frequency of excitation signal changed to ω_3 , controller parameter T_I changed to T_{I3} . The evaluated Phase Margin γ_3 is equal to its desired value.

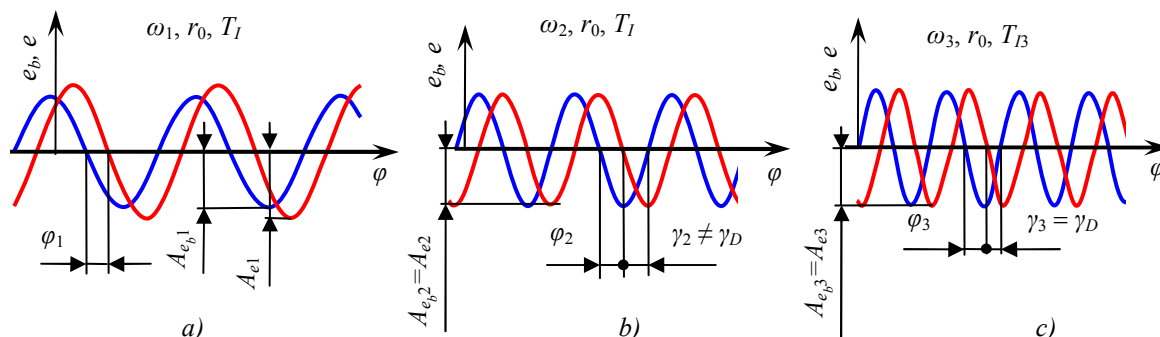


Fig. 2. Three main steps in process of PI controller tuning based on Phase Margin control quality indicator (depicted is tuning of the parameter T_I only) – amplitudes of the signals has the signal name in the indices

control quality indicators are Phase Margin (γ), Gain Margin (m_A), Maximum Sensitivity (M_s), Phase Margin Crossover Frequency (ω_γ), Gain Margin Crossover Frequency (ω_π), and Maximum Sensitivity Crossover Frequency (ω_s). The first three control quality indicators are dimension-less, the remaining indicators are of the dimension of s^{-1} .

The tuning is done in several steps that are depicted in Figure 2. For illustrative purposes, the tuning of only one controller parameter is shown there. In a starting situation (Fig. 2a), the frequency ω_1 of the exciting signal is not of such a value, when the phase delay φ_1 corresponds to the Phase Margin. The frequency is then changed gradually in order to achieve the state when $A_{e2} = A_{eb2}$, i.e. the state when phase delay corresponds to the Phase Margin γ , but is not equal to its required value γ_D (Fig. 2b). The controller parameters are then changed simultaneously with frequency changes, in order that the equality of magnitudes $A_{e3} = A_{eb3}$ remains fulfilled and to reach the Phase Margin $\gamma = \gamma_D$ (Fig. 2c).

The evaluation done in closed loop has a great advantage - the controller can eliminate some nonlinearities in the plant, so the measured responses are more similar to sinusoidal responses than the equal responses evaluated in open loop, or at least, it makes the shape of signals e_b and e similar to each other, so their relative error when both signals are compared with corresponding sinusoidal signal is the same (Vrána, Šulc, and Oswald, 2010).

The accuracy of evaluation of actual control quality indicators depends on the amplitude of harmonic excitation b . Its amplitude must be chosen so that the amplitude of response on this excitation must be at least comparable to amplitude of noise in order to be measurable. Also, it should not exceed the maximal allowed variance. The amplitude of harmonic excitation b should be manipulated such a way to its response not overcome any of these two limits.

3. RULES FOR CHANGING CONTROLLER PARAMETERS

The rules for controller parameter changes and of excitation frequency changes follow from the definitions of the used control quality indicators. The definition of every indicator can be converted into the triplet consisting of frequency ω , magnitude M , and phase angle φ . For most of the indicators, one value is fixed, one can be set as the required one, and the last one follows from those two defined values.

E.g. Phase Margin γ is defined as

$$\gamma = 180^\circ - \varphi_\gamma, M_\gamma = 1, \quad (1)$$

where φ_γ is the phase angle between the input and the output harmonic signals to and from the open control loop and M_γ is their magnitude. It follows from this statement that the frequency ω should be changed in order to maintain $M_\gamma = 1$ and the controller parameters should be manipulated such that the phase φ_γ reaches its desired value $\varphi_{\gamma D}$, which is

$$\varphi_{\gamma D} = 180^\circ - \gamma_D, \quad (2)$$

where γ_D is the desired value of the Phase Margin.

Similarly, the Gain Margin is defined as

$$m_A = \frac{1}{M_\pi}, \varphi_\pi = 180^\circ, \quad (3)$$

where M_π is the magnitude between the input and the output harmonic signals to and from the open control loop and φ_π is their phase angle. It follows from this statement that the frequency ω should be changed in order to maintain $\varphi_\pi = 180^\circ$ and the controller parameters should be manipulated such that the magnitude M_π reaches its desired value $M_{\pi D}$, which is

$$M_{\pi D} = \frac{1}{m_{AD}}, \quad (4)$$

where m_{AD} is the desired value of the Gain Margin.

Maximum Sensitivity M_s is defined as

$$M_s = \min \sqrt{\frac{1}{M_\sigma^2 - 2M_\sigma \cos \varphi_\sigma + 1}}, \quad (5)$$

where φ_σ is the phase angle between the input and the output harmonic signals to and from the open control loop and M_σ is their magnitude. It follows from this statement that the frequency ω should be changed in order to maintain M_s at its minimum, which makes the evaluation of the Maximum Sensitivity more time demanding as no direct condition for φ_σ and M_σ exists. One of the possible ways of obtaining the Maximum Sensitivity experimentally is described in Crowe and Johnson (2005).

The tuning rules can be composed in various ways depending on which control quality indicators are important for controlled plant/process. The optimal number of chosen control quality indicators is the same as the number of controller parameters. For a PID controller with the transfer function

$$G_C = \frac{r_D s^2 + r_0 s + r_I}{s}, \quad (6)$$

the tuning rules can be

$$r_I(k+1) = \frac{\varphi_{rD}}{\varphi_\gamma(k)} r_I(k), \quad (7)$$

$$r_0(k+1) = \frac{M_s(k)}{M_{sD}} r_0(k), \quad (8)$$

$$r_D(k+1) = \frac{M_{\pi D}}{M_\pi(k)} r_D(k), \quad (9)$$

where k is the order of the iterative tuning step,

while the conditions for excitation frequency changes are

$$\omega(k^*+1) = \frac{1}{M_\gamma(k^*)} \omega(k^*) \quad \text{when evaluating } \varphi_\gamma(k), \quad (10)$$

$$\omega(k^*+1) = \frac{-180^\circ}{\varphi_\pi(k^*)} \omega(k^*) \quad \text{when evaluating } M_\pi(k), \quad (11)$$

where k^* is the order of the iterative frequency change,

Alternatively, the following rules can be used

$$r_I(k+1) = \frac{1}{M_\gamma(k)} r_I(k), \quad (12)$$

$$r_0(k+1) = \frac{M_{\pi D}}{M_\pi(k)} r_0(k), \quad (13)$$

$$r_D(k+1) = \frac{M_{240D}}{M_{240}(k)} r_D(k), \quad (14)$$

where M_{240} is the magnitude between the input and the output harmonic signals to and from the open control loop when the phase angle between them is $\varphi_{240} = -240^\circ$. Details about this control quality indicator can be found in Vrána (2011).

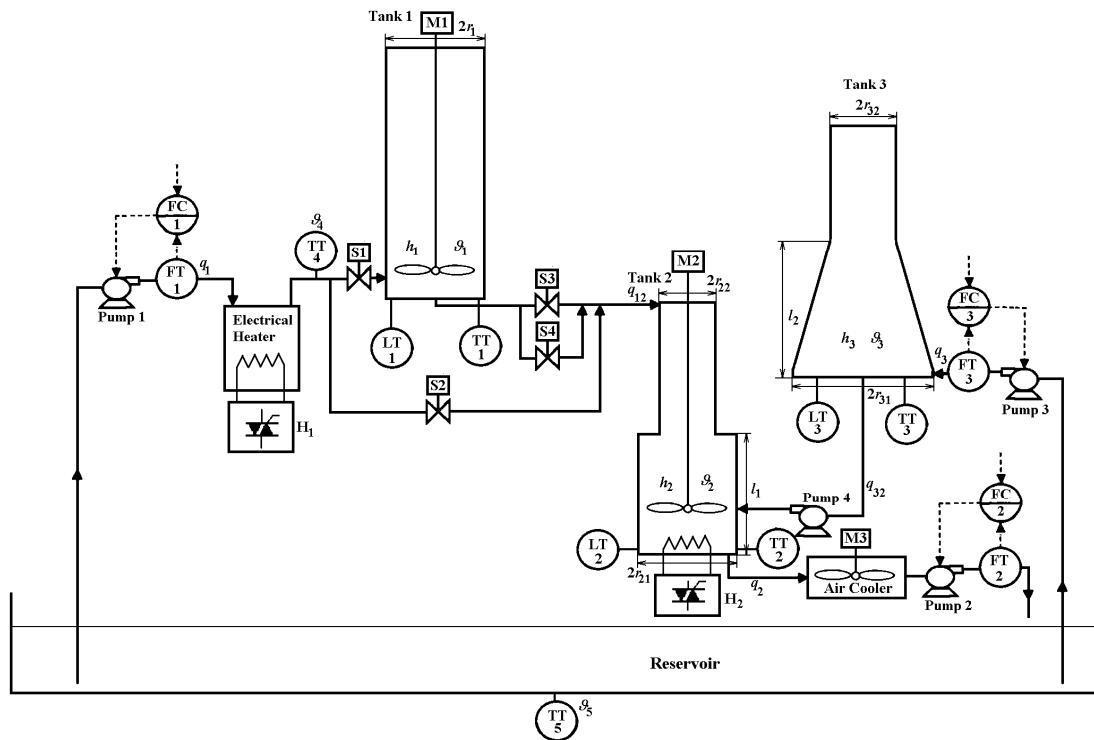


Fig. 3. Scheme of Tank Cascade used for simulation testing, tank height 0.8 m, $l_1 = 0.4$ m, $l_2 = 0.4$ m (figure used with agreement of authors of Hlava and Šulc (2008))

In this case, the conditions for excitation frequency changes are

$$\omega(k^* + 1) = \frac{\varphi_{\gamma D}}{\varphi_{\gamma}(k^*)} \omega(k^*) \text{ when evaluating } M_{\gamma}(k), \quad (15)$$

$$\omega(k^* + 1) = \frac{-180^\circ}{\varphi_{\pi}(k^*)} \omega(k^*) \text{ when evaluating } M_{\pi}(k), \quad (16)$$

$$\omega(k^* + 1) = \frac{-240^\circ}{\varphi_{240}(k^*)} \omega(k^*) \text{ when evaluating } M_{240}(k), \quad (17)$$

When a PI controller is tuned and tuned rules are set as

$$r_I(k+1) = \frac{1}{M_{\gamma}(k)} r_I(k), \quad (18)$$

$$r_0(k+1) = \frac{\omega_{\pi D}}{\omega_{\pi}(k)} r_0(k), \quad (19)$$

both control quality indicators are evaluated simultaneously, so there is only one rule (15) used for excitation frequency changes.

Similarly, the tuning rules can be chosen as

$$r_I(k+1) = \frac{\omega_{\gamma D}}{\omega_{\gamma}(k)} r_I(k), \quad (20)$$

$$r_0(k+1) = \frac{M_{\pi D}}{M_{\pi}(k)} r_0(k), \quad (21)$$

when rule (16) is used for excitation frequency changes. This set of rules makes the tuning procedure less time demanding because $\omega_{\pi} > \omega_{\gamma}$.

To evaluate the control quality indicators in a closed control loop, the comparative evaluation was developed (Vrána, Šulc, and Oswald, 2010).

4. TUNING RESULTS

The scheme of tank cascade whose simulation model was used for tuning algorithm testing is shown in Figure 3. Water level h_2 of Tank two was controlled. Tank Two was fed through Tank Three, while Tank One was not used. The cascade contains pumps between Tank Three and Tank Two and at the output of Tank Two instead of using valves. This allows the simulation of any type of valve with various opening characteristics. In presented case, the flow through these two pumps was manipulated according the equation

$$Q_x = Q_0 \sqrt{\frac{h_x}{h_{x0}}}, \quad (22)$$

where Q_x is the output flow rate from the x th tank

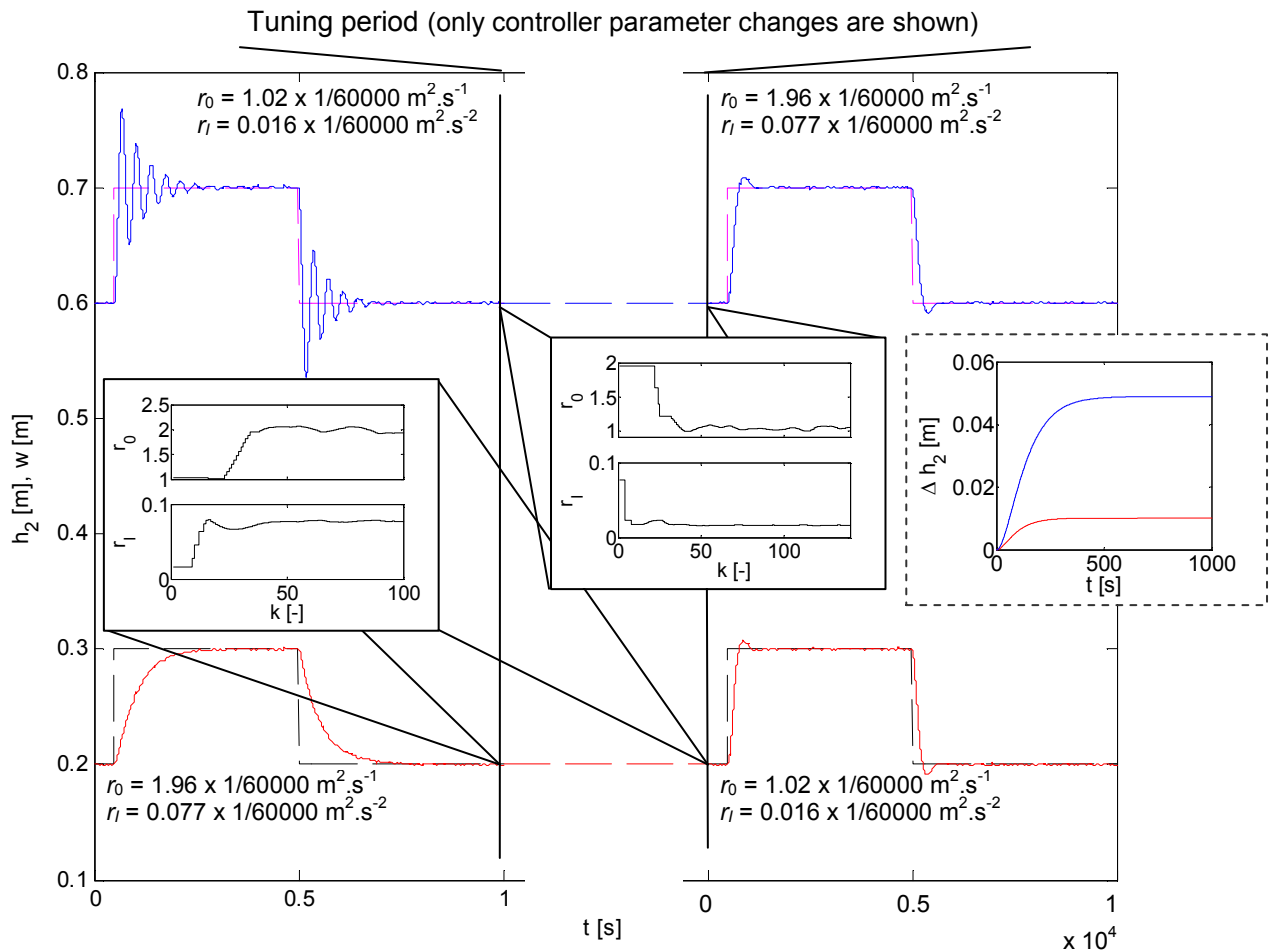


Fig. 4. An example of tuning procedure and obtained results

Q_0 is the steady-state output flow rate,
 h_x is water level in x th tank,
 h_{x0} is the steady-state water level in x th tank.

The usual square root valve characteristics is simulated when the flow through the pumps at the output of the tanks is manipulated according to (22).

Figure 4 shows the responses to the setpoint change before and after tuning in two different steady states. In the right part of the figure bordered with dashed line, the step responses of water level h_2 of the controlled model are shown. The step change was made in the flow rate of water flowing into Tank Three and it was increased by $0.1 \text{ l}\cdot\text{min}^{-1}$. The steady states of h_2 before the step change were $h_{2-1} = 0.2 \text{ m}$ (red line) and $h_{2-2} = 0.6 \text{ m}$ (blue line).

To probe the capabilities of the new tuning method, the procedure of increasing and decreasing the setpoint is done in order to compare the used controller setting before and after tuning. The setpoint is decreased by 0.1 m and when the transient is finished, the setpoint is then returned back to its original value. The course of the setpoint is marked with violet and black dashed line respectively. The same experiment is repeated after the controller is retuned.

The first experiment is made in the steady state $h_{2-1} = 0.2 \text{ m}$ (red line) with the initial controller settings (left bottom part of the figure) that shows that the step responses are sluggish. Then the controller is tuned (tuning period is marked by the dashed line and by course of the plots of the controller parameter changes). The desired controller quality indicator values were Phase Margin $\gamma = 60^\circ$ and crossover frequency $\omega_\gamma = 0,007 \text{ rad}\cdot\text{s}^{-1}$. The experiment done after tuning shows a faster response with a small overshoot (bottom right part of the figure).

Then the setpoint was changed to $h_{2-2} = 0.6 \text{ m}$ (blue line). The experiment shows that the setting, which is optimal for steady state $h_{2-1} = 0.2 \text{ m}$, is not optimal for steady state $h_{2-2} = 0.6 \text{ m}$, because the response oscillates too much (top left part of the figure). The controller is then tuned again (tuning period is marked by the dashed line and by course of the plots of the controller parameter changes). The desired controller quality indicator values remained the same, Phase Margin $\gamma = 60^\circ$ and crossover frequency $\omega_\gamma = 0,007 \text{ rad}\cdot\text{s}^{-1}$. After the controller tuning, the last experiment shows a non-oscillating response with a small overshoot (top right part of the figure).

Both responses after controller tuning are similar, which confirms that in both cases the desired values of the control quality indicators were obtained (with some precision).

The small values of controller parameters are caused by dimensions used in the controlled plant model, especially of the pump flow, and by recalculating them to SI units ($1 \text{ l}\cdot\text{min}^{-1} = 1/60 \text{ 000 m}^3\cdot\text{s}^{-1}$)

5. INFLUENCE OF NOISE AND DISTURBANCES

A noise is present when control the real loop. Its influence depends on the ratio of the amplitude of noise to the

amplitude of response on the harmonic excitation. If the amplitude of response is comparable to amplitude of noise the controller parameter values do not reach the stable value but remain slowly oscillating around the optimal values. The variability of controller parameter decreases with decreasing of the ratio of the amplitude of noise to the amplitude of response on the harmonic excitation. The small variations in controller parameter values are still better than badly tuned controller.

The influence of disturbances depends on how many sinusoidal waves are evaluated to obtain actual control quality indicator values. If the disturbances occur infrequently, their influence is low even when low number of sinusoidal waves is evaluated, while frequent occurrence of disturbance needs bigger number of sinusoidal waves to be evaluated, which on the other hand makes the tuning more time demanding. The influence of disturbances may also corrected by change of desired values of control quality indicators.

6. CONCLUSIONS

The tuning based on the control quality indicators has several advantages over many of the existing tuning methods. Controller retuning can be performed with no controller disconnection or other control function restrictions. It uses no model or any other type of controlled plant behaviour description. The nonlinearities contained in the plant are respected, because they are reflected in measured data.

The tuning method is based on techniques that are usually known to controller operators, which makes it easy applicable. No special control theory knowledge is necessary. The operator can influence the results by setting the desired values of the control quality indicators. The tuning can be done continuously or on demand. It is necessary to set some initial parameters manually; these parameters are the initial controller parameters, the initial excitation frequency and the initial excitation signal amplitude.

The testing of the tuning method on a simulation model of three-tank cascade proved its usability and stability of the tuned parameter course. The time necessary to obtain new controller parameter values depends on the properties of controlled plants, chosen control quality indicators for controller parameter optimization, and how much the optimal parameter values differ from the actual values.

ACKNOWLEDGEMENTS

This work was supported by Ministry of Education, Youth and Sports, grant No. MSM6840770035, and by the Grant Agency of the Czech Technical University in Prague, grant No. SGS10/252/OHK2/3T/12.

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