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Simultaneous Robust, Decoupled Output Feedback Control for Multivariate Industrial Systems

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ABSTRACT This paper proposes a simultaneous robust decoupled output feedback control approach for multivariate industrial processes with parameter uncertainties. Based on the desired control performance indicators, the expected transfer function of the closed-loop multivariate system is configured as a nonsingular diagonal matrix. Using coprime factorization theory, the weighting functions are selected and the parameterization matrix and controller are designed and calculated to achieve simultaneous robust decoupled control that takes into consideration parameter uncertainties. The performance and effectiveness of the proposed approach is demonstrated using a case study based on the crown-thickness control system of the hot strip mill processes.

INDEX TERMS Multivariable control system, robust control, system decoupling, industrial processes.

I. INTRODUCTION

Due to increasing demands on production quality and system performance, operation safety and system reliability have become critical aspects, which have led to much attention both in the academic and industrial fields. Furthermore, large-scale complex processes with strong integration of control loops and subsystems are the state-of-the-art in many modern industrial systems. For example, a large number of control loops are found in the rolling mill process, where there are hundreds of sensors, actuators, and controllers [1]. In larger, more complex industrial systems, it is common that most of the processes variables that are to be controlled require multivariate control systems. Although PI/PID methods are still widely used for industrial process control [2]–[4], especially in cascade control loops, their application is limited in the following cases: 1) where high production quality and flexibility over a wide range of operating conditions are required [5]; 2) where there are large changes in process conditions due to operational changes [6], component malfunction, or disturbances that lead to a significant plant-model mismatch [7]; and 3) where there is strong coupling between the different components of the system [8]. These limitations can cause issues with variable control using the original controller. Driven by these needs, great effort has been made both in academic research and engineering application to develop advanced control systems that can handle these problems, including, robust H∞-control and decoupling control.

Robust control, especially H∞-control theory, has attracted researchers' attention since its appearance in the control engineering field. For MIMO systems, multivariate robust controller design can be formulated as an H∞ optimization problem based on the general formulation of the control problem [9]. Controller synthesis and parameter design is a hot research topic for multivariate systems [10]–[12]. Meanwhile, due to the complexity of industrial system and strong coupling between different subsystems, decoupling control approaches for multivariate systems have been developed and implemented in the past few years [13]–[15].

However, few researchers have considered combining these two approaches, which could provide a solution for the problem of parameter uncertainty. Fragoso *et al.* [16] compared the performance of decoupling control and H∞ multivariable robust control for a lab-scale wind turbine.

They showed, using both theoretical and experimental results, that both robust and decoupling control are required, especially since decoupling control needs to consider model uncertainties, while H∞ control introduces strong interactions.

Thus, this paper seeks to develop an approach for the design and realization of a robust, decoupled control approach for MIMO system that can guarantee closed loop stability and control performance. Furthermore, the proposed approach will be tested on the crown-thickness control system of the hot strip mill process, which is a highly coupled system.

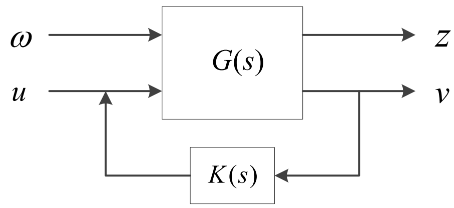

FIGURE 1. **The generalized robust control problem.**

II. SIMULTANEOUS ROBUST, DECOUPLED OUTPUT FEEDBACK CONTROL APPROACH

A. BACKGROUND

Fig. 1 shows the general model of the H∞ robust control problem, where $G(s)$ is the generalized plant, $K(s)$ the feedback controller, v the measured variables, u the control signals, ω the exogenous signals, and z the error variables.

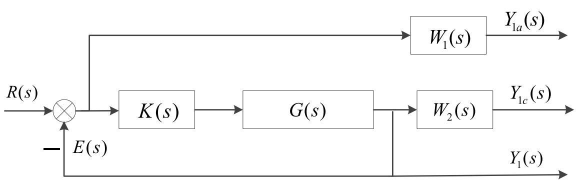

FIGURE 2. **The robust control system based on the mixed sensitivity problem.**

Although the optimal H∞ control problem cannot be solved using a standard systematic design procedure [17], there are solutions for the suboptimal problem. One such method is the mixed sensitivity method shown in Fig. 2, where $G(s) \in \mathrm{RH}_\infty$ is the transfer function matrix for the multivariable square system; $K(s) \in \mathrm{RH}_\infty$ is the robust controller that is to be designed; RH_∞ is the set of all proper and real-rational stable transfer matrices; $R(s)$ is the reference input; $Y(s)$ the system output; and $E(s)$ the error vector. The weighting functions $W_1(s)$ and $W_2(s)$, need to be designed based on the desired control performance, using such criteria as the output tracking behavior and the overall system dynamic behavior.

When there are multiplicative disturbances in the system, in order to obtain the minimized tracking error, the stabilized controller should satisfy the following robust performance indicator:

$$\|W_1(s)S(s)\|_\infty < 1 \tag{1}$$

where $S(s)$ is the sensitivity function which shows the magnitude of the tracking error, and is defined as:

$$S(s) = [I + G(s)K(s)]^{-1} \tag{2}$$

When we focus on the robust dynamic performance of system, the controller should satisfy the following robust performance indicator:

$$\|W_2(s)T(s)\|_\infty < 1 \tag{3}$$

where $T(s)$ is the complementary sensitivity function which reflects the influence on the system of the uncertainty and disturbance, and is defined as

$$T(s) = G(s)K(s)[I + G(s)K(s)]^{-1} \tag{4}$$

Then, the mixed sensitivity function and complementary sensitivity function are

$$\begin{aligned}
&T(s) = G(s)K(s)[I + G(s)K(s)]^{-1}\\
&T(s)[I + G(s)K(s)] = G(s)K(s)\\
&I + T(s)[I + G(s)K(s)] = I + G(s)K(s)\\
&[I + G(s)K(s)]^{-1} + T(s) = I\\
&T = I - [I + G(s)K(s)]^{-1} = I - S(s)\\
&S(s) = I - T(s)
\end{aligned} \tag{5}$$

B. THE SIMULTANEOUS ROBUST, DECOUPLED CONTROL APPROACH

In general, consider a stabilized and detectable nominal system $G(s)$, which has a state-space realization of the form

$$G(s) = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{6}$$

Let $G(s) = U(s)V^{-1}(s) = \hat{V}^{-1}(s)\hat{U}(s)$, be the right-coprime factorization and left-coprime factorization of $G(s)$ over RH_∞. Then, the set of all proper controllers based on the Youla-Kučera parameterization [18] that achieve internal stability can be parameterized as

$$\begin{aligned}
&K(s) = [X(s) + V(s)Q(s)][Y(s) - U(s)Q(s)]^{-1},\\
&Q(s) \in RH^\infty\\
&\qquad \det[Y(s) - U(s)Q(s)] \neq 0
\end{aligned} \tag{7}$$

where $X(s)$, $V(s)$, $Y(s)$, and $U(s) \in \mathrm{RH}_\infty$ satisfy Bezout's identity

$$U(s)X(s) + V(s)Y(s) = I \tag{8}$$

and $Q(s) \in \mathrm{RH}_\infty$ is the Youla-Kučera parameterization matrix.

Theorem 1: Let $G(s) \in RH_\infty$ be a given minimum phase, stabilizable, and detectable square nominal system. If the closed loop system can be reconfigured as a nonsingular stabilized diagonal matrix, then the controller determined using $||W_1(s)S(s)||_\infty < 1$ is a stabilized robust controller.

Proof: When the closed loop system is reconfigured as a nonsingular stabilized diagonal matrix, then the complementary sensitivity function is a stable diagonal matrix, in that case, the system is decoupled. If the weighting function $W_1(s)$ is properly selected, the following robust performance indicator can be satisfied

$$\|W_1(s)S(s)\|_\infty = ||W_1(s)[I - T(s)]||_\infty < 1 \tag{9}$$

Then, let

$$\begin{aligned} &G(s) = U(s), \quad X(s) = 0,\ V(s) = I,\ Y(s) = I \\ &U(s) \in RH^\infty, \quad V(s) \in RH^\infty, X(s) \in RH^\infty, Y(s) \in RH\infty \end{aligned} \tag{10}$$

Substituting Equation (10) into Equation (7), gives

$$\begin{aligned} K(s) &= [X(s) + V(s)Q(s)][Y(s) - U(s)Q(s)]^{-1} \\ &= Q(s)[I - G(s)Q(s)]^{-1} \end{aligned} \tag{11}$$

Since the system has been reconfigured as decoupled and system output is also set to the desired control performance, then based on Equations (4) and (11), the parameterization matrix $Q(s)$ is

$$\begin{aligned} &T(s) = G(s)K(s)[I + G(s)K(s)]^{-1} = G(s)K(s)S(s) \\ &\quad = G(s)Q(s)[I - G(s)Q(s)]^{-1}S(s) \\ &G^{-1}(s)T(s)S^{-1}(s) = Q(s)[I - G(s)Q(s)]^{-1} \\ &Q(s) = G^{-1}(s)T(s)S^{-1}(s)[I - G(s)Q(s)] \\ &Q(s)[I + G^{-1}(s)T(s)S^{-1}(s)G(s)] = G^{-1}(s)T(s)S^{-1}(s) \\ &Q(s) = [I + G^{-1}(s)T(s)S^{-1}(s)G(s)]^{-1}G^{-1}(s)T(s)S^{-1}(s) \\ &\quad = [I + G^{-1}(s)[S^{-1}(s) - I]G(s)]^{-1}G^{-1}(s)T(s)S^{-1}(s) \\ &\quad = [I + G^{-1}(s)S^{-1}(s)G(s) - I]^{-1}G^{-1}(s)T(s)S^{-1}(s) \\ &\quad = G^{-1}(s)S(s)G(s)G^{-1}(s)T(s)S^{-1}(s) \\ &\quad = G^{-1}(s)S(s)[S^{-1}(s) - I] = G^{-1}(s)[I - S(s)\} \\ &\quad = G^{-1}(s)T(s) \end{aligned} \tag{12}$$

Therefore, the controller determined by this parameterization and Equation (11) is a robust controller. Furthermore, since the closed loop system transfer matrix is reconfigured as a nonsingular stabilized diagonal matrix, $T(s)$ is stable and diagonal. Thus, the closed-loop system is also decoupled, which implies that a simultaneous robust, decoupled controller is obtained. ***Q.E.D.***

Corollary 1: Consider a standard feedback control loop consisting of a given stabilizable nonsingular square MIMO system $G(s) \in \mathrm{RH}_\infty$ and a controller $K(s) \in \mathrm{RH}_\infty$. If the weighting functions $W_1(s)$ and $W_2(s)$ are selected to be nonsingular diagonal matrix, then, from Theorem 1, the robust controller $K(s)$ will be also a decoupled controller, satisfying the control performance by simultaneously taking into consideration the uncertainty and tracking error.

Proof: The proof is straightforward. From Equation (5), we get

$$\begin{aligned} Y_{1c}(s) &= W_2(s)T(s)R(s) \\ Y_{1a}(s) &= W_1(s)S(s)R(s) \end{aligned} \tag{13}$$

Since $T(s)$ and $W_2(s)$ are diagonal matrices, the product of these two matrices is also diagonal. Thus, the system outputs are decoupled against uncertainty. Furthermore, since $T(s)$ is diagonal, then $S(s)$ should also be a diagonal matrix. As well, since $W_1(s)$ is diagonal, then the product $W_1(s)$ and $T(s)$ is also diagonal, which implies that the system outputs and tracking error are decoupled. ***Q.E.D.***

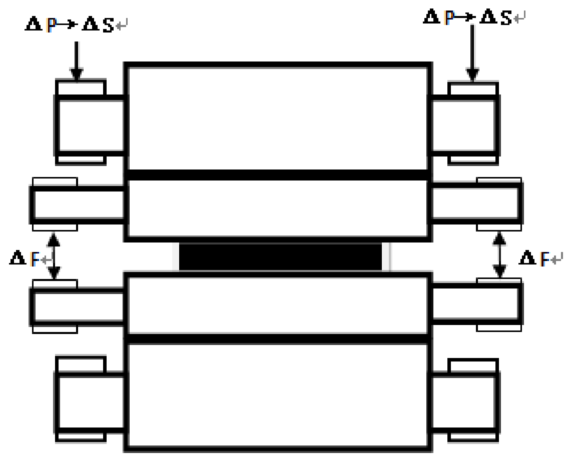

FIGURE 3. The diagram of simultaneous action of rolling force and bending force.

III. CASE STUDY ON A MULTIVARIATE ROLLING MILL SYSTEM

A. GENERAL DESCRIPTION OF THE CROWN-THICKNESS CONTROL SYSTEM IN THE HOT STRIP MILL PROCESS

In the hot strip mill production, strip quality is one of the most important factors for consumer satisfaction when selecting competing products. It is usually expressed in term of such variables as the strip thickness, the strip flatness, and strip width. Since the strip rolling process is the last production step in the long manufacturing steel process, it is especially important to maintain stable production quality using a predesigned control system in the hot/cold strip mill process. Therefore, the thickness of the strip [19], which is mainly controlled by the automatic gauge control (AGC) subsystem, and the crown of the strip [20], which is mainly controlled by the hydraulic bending roll (HBR) subsystem, can be defined as two key controlled factors for this system. However, due to the strong coupling effect of the different control subsystems, it is difficult to achieve the desired control performance by merely focusing on each subsystem independently. As shown in Fig. 3, the HBR system is influenced by AGC system based on the *spring equation* of the strip mill process,

$$h = S + \frac{P}{C} \tag{14}$$

where C is the equivalent stiffness of the mill stand, h the actual exit thickness, P the rolling force, and S the roll gap [21]. The roll gap difference ΔS is the key parameter to be controlled by the AGC system, which will lead to the change in the rolling force ΔP based on the spring equation. This results in parameter fluctuation of the roll horizontal bending deflection and shear deflection, which in turn causes

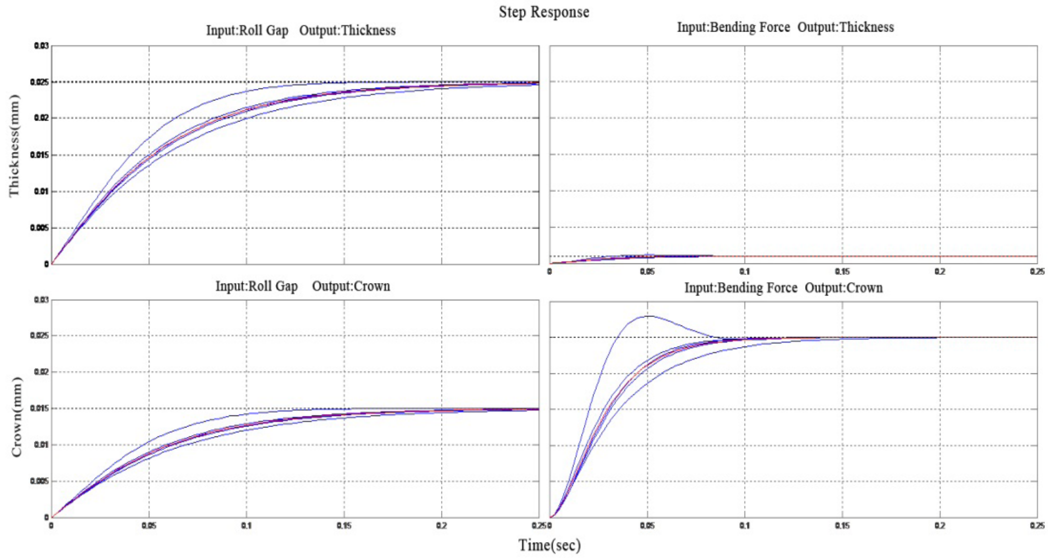

FIGURE 4. **The step response of the system output by coupling effect and parameter uncertainty.**

deviations in the strip crown. On the other hand, in the strip crown control system, the key controlled parameter is the change in the bending forces ΔF, which will compensate for roll deflection, but can lead to the deviation of the rolling force as an external disturbance and then cause a parameter coupling effect in the AGC system. Based on the above analysis, the crown-thickness control system can be defined as a typical multivariate system with strong coupling effects.

Based on past research [22], [23] into the crown-thickness control system, a transfer function model of the coupled system is

$$\begin{bmatrix} \Delta h \\ \Delta CR \end{bmatrix} = G(s) \begin{bmatrix} \Delta S \\ \Delta F \end{bmatrix} \tag{15}$$

where ΔCR is the change in the crown thickness and Δh is the change in strip thickness.

Using standard system identification theory [24], the parameters of the hot strip rolling mill for a nominal set point of 1700 mm and a rolling speed of 13 m/s can be determined as [23]:

$$\begin{aligned} &\begin{bmatrix} \Delta h \\ \Delta CR \end{bmatrix} \\ &= \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} \Delta S \\ \Delta F \end{bmatrix} \\ &= \begin{bmatrix} \dfrac{0.00025s + 0.025}{0.00075s^2 + 0.065s + 1} & \dfrac{0.001}{0.0002s^2 + 0.03s + 1} \\ \dfrac{0.00025s + 0.025}{0.00075s^2 + 0.065s + 1} & \dfrac{0.025}{0.0002s^2 + 0.03s + 1} \end{bmatrix} \\ &\quad \times \begin{bmatrix} \Delta S \\ \Delta F \end{bmatrix} \end{aligned} \tag{16}$$

In practice, the rolling speed can vary between 10 and 16 m/s, leading to the potential for a 20% change in the parameters [22]. Generally speaking, uncertainty can be either additive or multiplicative. In the crown-thickness system, the uncertainty is multiplicative, since it originates from the rolling speed. Fig. 4 shows the output of the system with parameter uncertainties using conventional PI controllers, under a unit step excitation. The upper right and lower left subfigures of Fig. 4 show the strong coupling effects between the two control systems. Furthermore, large overshoots due to the parameter uncertainties can be seen. These observations suggest that a simultaneous robust, decoupled control approach is needed to improve the control performance.

B. CONTROL IMPLEMENTATION

The implementation of the simultaneous, robust, decoupled controller follows the steps of Theorem 1.

1) Step 1: Determine the Desired Configuration

The closed loop transfer function matrix is reconfigured as a diagonal matrix based on the desired decoupling performance, where the zeros/poles should satisfy the system response. Since the crown-thickness system, which contains a servo hydraulic and an inertia components, should have a settling time of less than 45ms [22], the complementary sensitivity function is

$$T(s) = \begin{bmatrix} \dfrac{1}{0.01s + 1} & 0 \\ 0 & \dfrac{1}{0.5(0.01s)^2 + 0.01s + 1} \end{bmatrix} \tag{17}$$

2) Step 2: Select the Weighting Function $W_1(s)$

The selection of weighting function depends mainly on the fact that its frequency bandwidth should be in line with the bandwidth of the complementary sensitivity function. The weighting function can be determined based on the step response and Bode diagram of $S(s)$. In such cases, $W_1(s)$ can

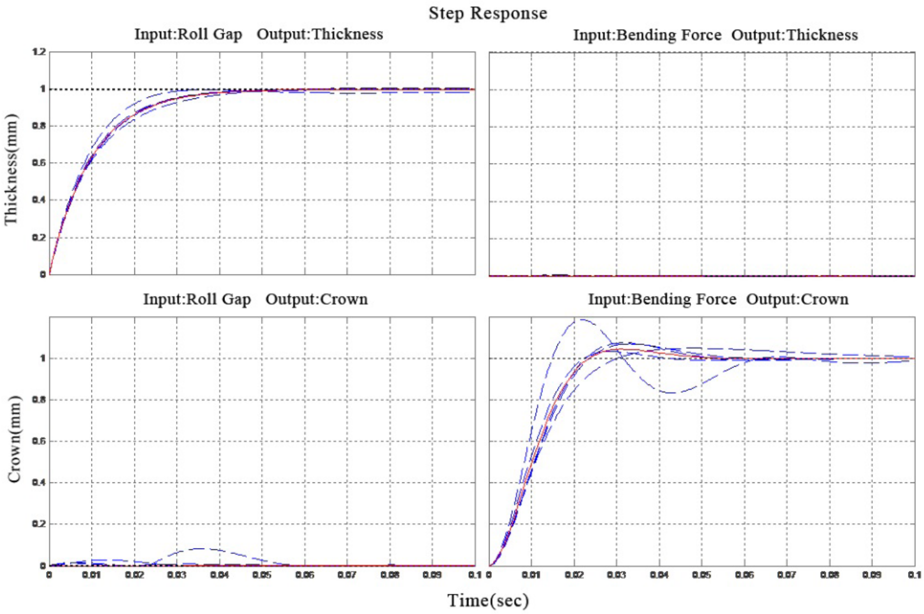

FIGURE 5. The step response of the system output with the designed simultaneous robust, decoupled controller.

be written as [25]

$$W_1(s) = \operatorname{diag}\left[\frac{\frac{s}{M}+\omega_0}{s+A\omega_0}\right] \tag{18}$$

where $A < 1$ is the maximal steady state error, such that when $A = 1$, the steady state error is 1.0%; $M > 1$ is the system response at the initial state $t = 0^+$, such that when $M = 100$, the system response for a step excitation is 1%; and ω_0 is the expected bandwidth, which determines the robust control performance after decoupling. If the desired settling time is 45 ms, then ω_0 can be determined as follows:

$$\begin{aligned} T_t &= \frac{2\pi}{\omega_c} = \frac{2\pi}{\sqrt{2}\omega_0} = \sqrt{2}\frac{\pi}{\omega_0} \le 45ms, \\ &\Rightarrow \omega_0 = \sqrt{2}\frac{\pi}{T_t} \\ \omega_0 &= 100 \text{ ms} \end{aligned} \tag{19}$$

where ω_c is the system cut-off frequency.

Based on the engineering requirements of the crown-thickness system, the required parameters can be defined as $A = 1$, $M = 100$, $\omega_0 = 100$ ms and

$$W_1(s) = \begin{bmatrix} \frac{0.001s+1}{0.01s+1} & 0 \\ 0 & \frac{0.001s+1}{0.01s+1} \end{bmatrix} \tag{20}$$

3) Step 3: Verify the Robust Control Performance

Robust control performance can be verified using Equation (9), which gives

$$||W_1(s)S(s)||_\infty = ||W_1(s)[I - T(s)]||_\infty = 0.7264 < 1 \tag{21}$$

4) Step 4

Obtain the Parameterization Matrix $Q(s)$ using Equation (12), based on the expected system control performance.

5) Step 5

Determine the Parameters for the Robust Controller $K(s)$ Using Equation (11).

C. RESULTS AND DISCUSSION

Fig. 5 shows the two outputs, thickness and crown thickness, as a function of time when the crown control system is perturbed by a unit step excitation for different working conditions, defined by the rolling speed. The solid line is the nominal system and the dashed lines are the system with parameter uncertainties. The top figures represent the response of the system to a step change in the steel thickness and the bottom figures represent the response of the system to a step change in the steel crown. We can see from the subfigure in upper right corner and lower left corner that there is almost no coupling effect in the crown thickness MIMO systems. It can be noted that the simulation environment and system parameters in Fig. 5 are consistent with Fig. 4. It can be seen in Fig. 5 that even under parameter uncertainties caused by the changeable rolling speed, the crown-thickness MIMO system outputs remains decoupled and robust, with a dynamic response that can track the reference signal in a very short time (settling time less than 45 ms).

IV. CONCLUSIONS

To deal with parameter uncertainties and coupling effects in multivariate industrial systems, this paper proposes a simultaneous robust, decoupled control approach based on coprime factorization theory and the mixed sensitivity function method. Since the control performance indicators can be obtained from an actual engineering system, the proposed approach is especially suitable for those multivariate industrial systems that can be converted into a square system with minimal phase and internal stability. These conditions can be easily satisfied by many plants in the process industry. The weighting functions are selected based on the desired control performance, while the controller is determined using the Youla-Kučera parameterization. The performance and effectiveness of the proposed control approach for robust, decoupled control performance is shown using the crown thickness MIMO system in hot strip mill process. Future work will examine online implementation of the proposed control structure.

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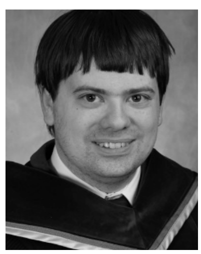

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