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Hysteresis Modeling and Inverse Feedforward Control of an AFM Piezoelectric Scanner Based on Nano Images*

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***Abstract*— Atomic force microscope(AFM) is a very important instrument with atomistic level resolution, which has been widely employed in the field of micro/nano technology. As a critical part of AFM system, the piezoelectric scanner exists many defects such as hysteresis, creep, and ease of vibration effects, which has become a bottleneck in its further development and application. In this paper, an image-based method by using polar coordinate is presented to model the piezoelectric scanner utilized in AFM, which can effectively avoid the troubles of data acquisition in AFM system. The parameters of its inverse model are identified by the Least-square method(LSM) and an inverse feedforward control strategy is developed. To verify the performance of this strategy, Being CSPM5500 AFM has been employed, the analysis and performance evaluation have been conducted in detail, which demonstrates that the novel hysteresis model and the image-based inverse feedforward control strategy presented in this paper possess a good performance for AFM nano imaging.**

***Index Terms*— Hysteresis modeling, feedforward control, atomic force microscope(AFM), polar coordinate, nano imaging.**

I. INTRODUCTION

In the field of micro/nano technology, AFM is a fundamental tool which plays the roles of “hand” and “eye” in applications concerning nano imaging, nanometer material analysis, nano manipulation, and so on. A three-dimensional piezoelectric scanner is usually employed in the AFM system to carry the sample material in the 3-D directions. Piezoelectric actuator has the advantages of fast response, high positioning precision, insensitive to temperature changes or the magnetic field effect [1], etc. Therefore, it is a hot research topic in recent years. Unfortunately, piezoelectric ceramic itself has many defects, such as hysteresis, creep, and vibration effects, which will block its further development and application.

Hysteresis is the main factor to affect the positioning precision [2], which will cause the distortion in scanning images. Numerous studies have been conducted to compensate the hysteresis, which can be divided into two main categories: feedback control strategy and model-based feedforward control strategy [3]. For instance, S. Salapaka designed and implemented of an H_∞ controller to demonstrate great improvement on performance [4]. Y. Wu made use of an inversion-based iterative control to obtain a better performance of the AFM system [5]. However, the feedback information of the system is obtained by some nano-sensors, such as linear variable differential transformer(LVDT), laser displacement sensor, and capacitance displacement sensor. Unfortunately, all of these nano-sensors should be installed into AFM systems, however, the space in the AFM system is very small. Moreover, it is expensive and unpractical to equip commercial AFM system with these nanoscale position sensors on the three-dimensional piezoelectric scanner.

Recently, many researchers are devoted to compensate the hysteresis through the model-based feedforward control strategy, whose main idea is to obtain mathematical model that closely describes the complex hysteresis behavior. In these models, there are two categories according to the modeling principle. The first one is constitutive model such as Jiles-Atherton(JA) magnetics model and homogenized energy model. These models are very easy to be understood, since they are built on the viewpoint of magnetization. Unfortunately, many parameters in these models which are sensitive to the working environment must be identified. The second one is phenomenological model, which is obtained by the mathematical approximation for the hysteresis. Most of these models, such as Bouc-Wen model [6], Duhem model [7], Dahl model [8], generic differential model [9], Maxwell Slip model [10], Preisach model [11], Prandtl-Ishlinskii(PI)model [12], are based on a large amount of data, among which the classical Preisach model(CPM) is the widely utilized model, since it can approximate to the actual input-output hysteresis relationship infinitely, but the parameters identifications are too complex, which has hampered the application of it. PI model is the improvement over the Preisach model, but its modeling process is too complicated, moreover, it is prone to generate burrs on the curve. Recently, some scholars have attempted to make use of the artificial neural network to

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model the hysteresis, which is easy to realize but impossible to meet the requirements of high precise positioning [13]. Meanwhile some researchers employ dynamic sliding mode control, which takes the hysteresis as the disturbance to the system. In order to ensure control system to achieve the switching surface, we need to know the uncertain range when designing control algorithm, actually, it is difficult to manage it.

The primary goal of this paper is to model hysteresis and control AFM piezoelectric scanner by employing the inverse feedforward control strategy, which will compensate the hysteresis of AFM system. As we mentioned before, besides the hysteresis, the creep and the vibration will also affect the performance of the piezoelectric ceramic scanner. Generally, the influence of creep will not happen until the experiment has been undertaken for a long time, while the vibration effect will not be actuated until the frequency of the input signal is high. Based on the above analysis, we can apply low frequency input voltage within a short running time to acquire some image data, which is utilized to model the hysteresis.

The rest of this paper is organized as follows. A novel and simple mathematic modeling method by using polar coordinate is proposed in Section II. Afterwards, an image-based parameter identification method will be presented in Section III. An inverse feedforward control strategy and some experimental results of images are presented in Section IV-V to illustrate the efficiency of the proposed method. Finally, the achievements and limitations of the conducted research are summarized in Section VI with future work indicated.

II. Modeling the AFM Piezoscanner Based on Polar Coordinate

A. The Working Principle of AFM

An AFM system is mainly composed of four parts: piezoelectric scanner, cantilever and probe system, laser detecting system, and controller [14]. An atomic force microscope obtains atomic resolution topography by using a nano-sized probe to detect tiny sample's surface, and its basic working principle is described in followings:

Just as shown in the Fig.1, a sample is put on the the piezoelectric scanner, then the probe tip is operated closely to it and the cantilever will deform, since there exist some atomic nonlinear forces between the sample surface and the probe tip. This tiny force can be measured by the laser detector, according to the relationship between the deformation and the atomic force. We can design the feedback control algorithm to adjust the displacement in the z direction of the piezoelectric scanner, which can keep the deformation of the cantilever at the setting value[15]. Then, we can obtain the height data of the sample at this position. For further information, we take the row as the fast scanning direction, and the column as the slow scanning direction. Then, as shown in the Fig.2, ϕ represents the scanning angle($\phi \in$[0°, 359°]), we change the relative position of the probe tip and the sample constantly, which can be used to obtain the up and down information of any position through recording of the coordinate and height of related point. That means if the scanning scale is set to 512pixel×512pixel, the probe should be moved by 1024 rows(bi-direction scanning mode should scan 1024 rows, single scanning mode only scan 512 rows). If we want obtain a 512pixel×512pixel nano image at the frequency of 2HZ, it will take about 4 minutes. According to the different characteristics of the samples, we have two types of working mode: tapping mode and contacting mode. Although the resolution of tapping mode is lower than contacting mode, but to some extent, it can reduce the viscous phenomenon that the sample adheres to the probe tip, which takes advantage of its amplitude to overcome the adhesion force between the probe tip and the sample. At the tapping mode, the force is vertical, the impacts of frictions and shear forces in horizontal direction on material surface are relatively smaller, which can avoid the damage to the sample by adjusting the probe tip in the scanning process. Therefore, we will try to employ tapping mode for soft and adhesive samples.

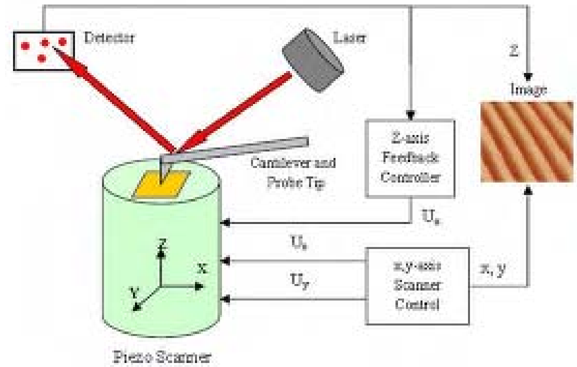

Fig. 1. The working principle of AFM system

Based on the above analysis, we can make a conclusion that the motion accuracy in the XY-direction and the feedback control accuracy in the Z-direction are the two main factors which will influence the imaging performance of the AFM system. In this paper, we will conduct research for the high precision position in the XY-direction.

B. Hysteresis Modeling Based on Polar Coordinate

It is well known that there are two difficulties in the hysteresis modeling for the implementation of feedforward control: The first one is the accuracy of the mathematical model, the second one is the identification procedure of its inverse model. In this paper, we present a hysteresis model to describe simply and appropriately the hysteresis in the AFM piezoelectric scanner. Observing the hysteresis curves

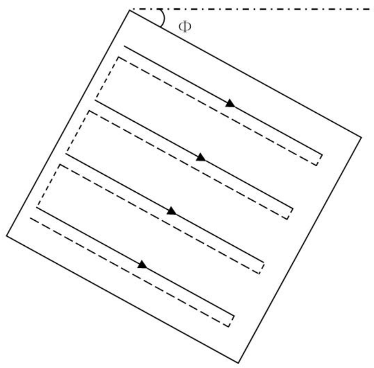

Fig. 2. The scanning path of AFM system

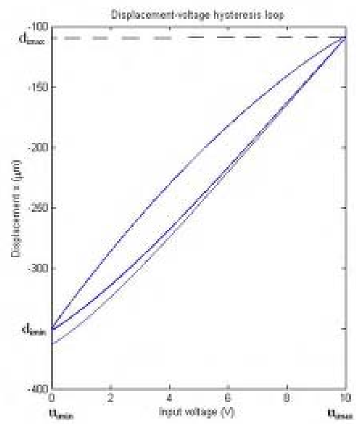

Fig. 3. Displacement-voltage hysteresis loop

in the Fig.3, we will find that the ascending curve and the descending curve are similar to the part of ellipse after rotation and transformation. According to this inspiration, the polar coordinate theory is applied to model the piezoelectric scanner hysteresis [16], which has the advantage that the proposed model simplifies the identification of its inverse model.

Just as shown in the Fig.2, the hysteresis model in the i^{th} loop is described as follows:

$$\begin{cases} u_{ai} = a_{ai}\sin(\theta_{ai})\cos(\alpha) + b_{ai}\cos(\theta_{ai})\sin(\alpha) + d_{0ai} \\ d_{ai} = a_{ai}\sin(\theta_{ai})\cos(\alpha) + b_{ai}\cos(\theta_{ai})\sin(\alpha) + u_{0ai} \end{cases} \tag{1}$$

$$\begin{cases} u_{di} = a_{di}\sin(\theta_{di})\cos(\alpha) + b_{di}\cos(\theta_{di})\sin(\alpha) + d_{0di} \\ d_{di} = a_{di}\sin(\theta_{di})\cos(\alpha) + b_{di}\cos(\theta_{di})\sin(\alpha) + u_{0di} \end{cases} \tag{2}$$

where, u_{ai}, u_{di} stands for the input voltage in the ascending curve and descending curve, respectively, d_{ai}, d_{di} stands for the output displacement respectively, and a_{ai}, a_{di}, b_{ai}, b_{di} are the coefficients of the presented model, u_{0ai}, d_{0ai} and u_{0di}, d_{0di} represent the center coordinate of the ellipse curve. θ_{ai} and θ_{di} are the bias angle of the ellipse in clockwise direction, α is the polar angle of the ellipse. The parameters of this model are listed as follows:

$$\begin{cases} u_{0ai} = \frac{u_{i\max} + u_{i\min}}{2} \\ d_{0ai} = \frac{d_{i\max} + d_{i\min}}{2} \\ \theta_{ai} = \arctan(\frac{d_{i\max} - d_{i\min}}{u_{i\max} - u_{i\min}}) \\ a_{ai} = \frac{\sqrt{(d_{i\max} - d_{i\min})^2 + (u_{i\max} - u_{i\min})^2}}{2} \end{cases} \tag{3}$$

$$\begin{cases} u_{0di} = \frac{u_{i\max} + u_{i\min}}{2} \\ d_{0di} = \frac{d_{i\max} + d_{i\min}}{2} \\ \theta_{di} = \arctan(\frac{d_{i\max} - d_{i\min}}{u_{i\max} - u_{i\min}}) \\ a_{di} = \frac{\sqrt{(d_{i\max} - d_{i\min})^2 + (u_{i\max} - u_{i\min})^2}}{2} \end{cases} \tag{4}$$

where u_{imax} and d_{imax} are the turning values of the i^{th} loop, u_{imin} and d_{imin} are the initial values of the i^{th} loop. In Equation (1), the range of α is determined by the curve of the outer loop. In this loop, the values of a_{a1} and a_{d1} can be obtained by the Equation (2), b_{a1} and b_{d1} can be identified by the least square method (LSM). Generally, AFM is set to single direction scanning mode. That means we only need to consider the ascending part. On the ascending curve, the error function is defined as follows:

$$E_a = \sum (d_{1fit} - d_{1act})^2, \alpha \in [-\pi, 0] \tag{5}$$

where d_{1fit}, d_{1act} represent the model fitting displacement and the actual displacement, respectively.

Strictly speaking, the ascending curve and the descending curve in the Fig.2 are not half of an ellipse, for simplicity, we assume that they are half of the ellipses. Therefore, all parameters of the outer loop can be obtained based on the above analysis. In fact, we cannot directly employ the outer loop model, since the scales of the input voltage may not be filled in practical applications. It is obvious that all the ascending curves are alike in different loops, so we can take advantage of their similarities when $i > 1$.

$$\begin{aligned} k_a &= a_{ai}/a_{a1} \\ b_{ai} &= k_a \times b_{a1} \end{aligned} \tag{6}$$

In order to implement an inverse feedforward control strategy, it is easy to obtain the inverse model according to the new developed model, which is described as follows:

$$\begin{cases} u_{ai} = a_{ai} \times \sin(\theta_{ai})\cos(\alpha) + b_{ai}\cos(\theta_{ai})\sin(\alpha) + d_{0ai} \\ d_{ai} = a_{ai} \times \cos(\theta_{ai})\cos(\alpha) - b_{ai}\sin(\theta_{ai})\sin(\alpha) + u_{0ai} \end{cases} \tag{7}$$

The parameters of this equation have been introduced above. However, this hysteresis model has been identified off-line. Yet, we know that the relationship between the input and output in the piezo scanner is varied when the frequency of the input voltage is changed. As a result, the correction will create an error between the desired and actual control output, and the identification of hysteresis model should be updated usually. To avoid this problem, it is desirable to consider online adaptive strategy for modeling and identifying the AFM piezoelectric scanner directly online.

III. Image-based Parameters Identification

The key issue of the hysteresis modeling is to obtain the parameters of the developed model. As mentioned above, in this paper, we scan a standard sample, then the displacement and voltage data can be extracted through the analysis of the nano images, since the period of the standard sample is given, the process of this method is expounded as follows:

Firstly, we acquire a piece of image by scanning a standard grating sample with the maximum scanning range(the XY-direction voltage is in the maximum scope), the period of this grating is preconditioned. Studying the obtained image, we will find that the image is not evenly distributed because of the hysteresis in the piezoelectric scanner. Just as shown in the Fig.4, the actual distance of any two adjacent featured points labeled by color triangles is fixed and completely periodic, since the two adjacent feature points are corresponding with two neighboring peak points of the grating sample. Based on above analysis, the input voltage and displacement data of the i^{th} feature point will be calculated by the formula as follows:

$$\begin{cases} d_i = iL_g \\ u_i = \frac{x}{S} \times V_r \end{cases} \tag{8}$$

where d_i, u_i represents the displacement and input voltage of the i^{th} feature point, respectively, x is the displacement measured by the image L_g, S represents the period of the calibration grating and the size of the grating sample employed in the experiment, respectively. Then, we plot it with MATLAB, and we will find that the relationship of the input voltage and displacement is not a straight line, just as shown in the Fig.3. In the ascending part, when the input voltage is increasing, the speed in the initial stage is increasing slowly than that in the ending stage, which will cause the distortion of the scanning image.

IV. Inverse feedforward control strategy

Just as the analysis which have conducted in the Section I, an inverse feedforward control strategy will be employed in this paper. Fig.5 shows the structure of inverse control strategy in an open-loop control system[17], $H(s)$ represents the hysteresis model of the piezo scanner, $H^{-1}(s)$ is the hysteresis inverse model. $y_d(k)$ is the desired motion trajectory of the piezoelectric ceramic scanner, and the $u(k)$ is the compensation voltage, which will be employed to drive the piezoelectric ceramic scanner. $y(k)$ is the output displacement. It is easy to find that the inverse model maps the desired signal into a compensation voltage signal, which will make the system output signal follow the desired input signal[18], which is expressed as follows:

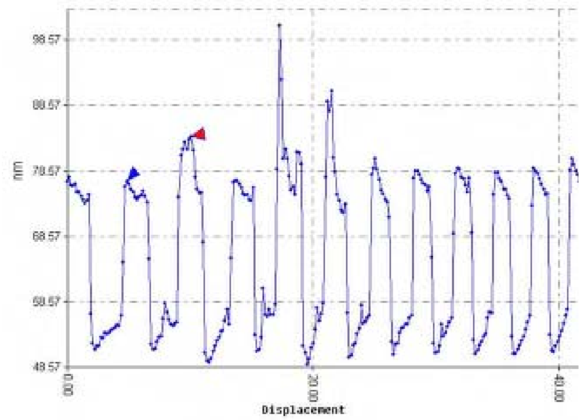

Fig. 4. Topography-pixel data of nano image

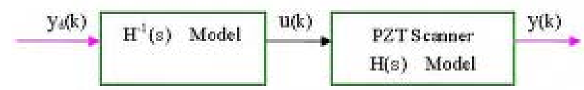

Fig. 5. The structure of inverse feedforward control system

$$y(k) = H[u(k)] = H[H^{-1}[y_d(k)]] \tag{9}$$

In the process of AFM image correction, the most important thing is to get the nonlinear sequence of voltage[19]. Just as shown in the Fig.3, in order to transfer the nonlinear relationship into linear relationship, we get the inverse control voltage according to the Equation (6), which will be used to actuate the piezo scanner to generate the same displacement.

V. Experimental Results and Discussion

In this section, the correction experiment on the hysteresis in AFM piezoelectric scanner will be undertook, and the strategy of inverse feedforward control based on the proposed model is employed. Afterwards, some experimental results are presented, which are used to evaluate the efficiency of the utilized method.

A. Materials and Equipments

To verify the performance of the presented image-based hysteresis modeling and correction strategy, we take advantage of the Being CSPM5500 AFM as the experimental platform, which has the horizontal scanning resolution of 0.2nm, and the vertical scanning resolution of 0.1nm, the XY-direction scanning scope can reach to 125μm × 125μm, and the movement range of Z direction can reach to 10μm. The control system has advanced image processing performance which is based on the DSP of TMS320DM642. The inverse feedforward control strategy is programmed by the Visual Studo.net, which is running in a control computer with the operating system of Windows XP, and the hardware configuration of Intel(R) Xeon(R) CPU W3503, 4GB RAM. After that, the nano-imaging tasks are conducted by using this AFM system to obtain some nano images (512pixel$\times$512pixel), which can evaluate the performance of the developed method. In this experiment, the input voltage of the piezo-scanner ranges from -180V to 180V, one dimension calibration grating is employed as the standard sample whose period is 278nm, the size is 83452nm$\times$83452nm.

B. Hysteresis modeling and inverse controller

As illustrated in Fig.4, the points marked by the color triangles are some feature points corresponding to the peak points of the sample. Then, the original data can be obtained by utilizing the strategy stated in SectionIII. After obtaining some original data, the parameters of the inverse model can be identified by utilizing the strategy stated in SectionIV. Afterwards, the hysteresis inverse model will be obtained and programmed by the Visual Studio.net, which will be used to control the scanning process in real-time. After that, the scanning experiments will be repeated for many times to evaluate the proposed hysteresis model and inverse control strategy accordingly.

C. Experimental results and discussions

In this experiment, a calibration grating with a period of 3,100nm is employed as the testing sample. The scanning range is set to 512pixel$\times$512pixel, and the AFM is set to the contact working mode. At the same time, the classical proportional-integral-derivative(PID) control algorithm is employed to the z-axis to keep the deformation of the cantilever at the setting value and the output constant. Fig.8 demonstrates the scanning results at the frequency of 1HZ(one line per second) and the scanning angle is set to 0°. As shown in the Fig.8(a), many distortions and the periodic of this grating cannot be observed from the image because of the hysteresis as marked in the image, the left part of the grating interval is obviously wider than the right part. In contrast, as shown in the Fig.8(b), the scanning results with hysteresis correction have proper and reasonable shape. That means the inverse feedforward control strategy has effectively attenuated the hysteresis of the piezo-scanner, and the scanned image indicates the actual topography of the grating sample accurately. The correction for the Y-axis has been conducted in the same way.

It is obvious that the image-based hysteresis modeling and correction strategy have improved the piezo-scanner and the AFM performance greatly. It should be noted that the actual ascending curve of hysteresis is shown as the Fig.9, as shown

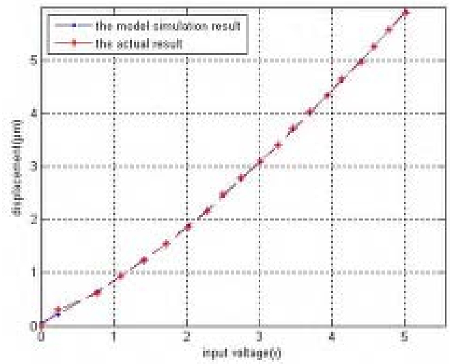

Fig. 6. The contrast diagram of actual data and modeling simulation data

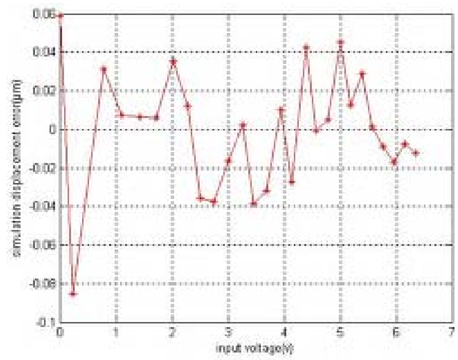

Fig. 7. Displacement error diagram

in this curve, the phenomenon of hysteresis is very serious in the interval of the origin point to the point A and the point B to the ending point. Generally, we ignore these two parts for simplicity if the requirement for the accuracy of positioning is not harsh. In this experiment, we pass over the scanning part of the voltage from [-180v, -162v] and [162v, 180v]. In fact, we should find out the two turning points of A and B, which can be used to carry out a section hysteresis modeling and compensation strategy to achieve the desired controlling results.

VI. Conclusion

This paper focuses on the hysteresis modeling and inverse control of AFM piezoelectric scanner. First of all, the common correction methods of hysteresis in piezoelectric actuator and the drawbacks have been summarized. Then, the working principle of AFM is introduced in a brief way, and a novel and simple mathematic modeling method by using polar coordinate is presented. Moreover, the specific steps of image-based parameters identification method have been listed. Afterwards, the principle of inverse feedforward control strategy is introduced. Finally, some experimental results are presented, and the analysis and performance evaluation have been conducted in detail, which indicate

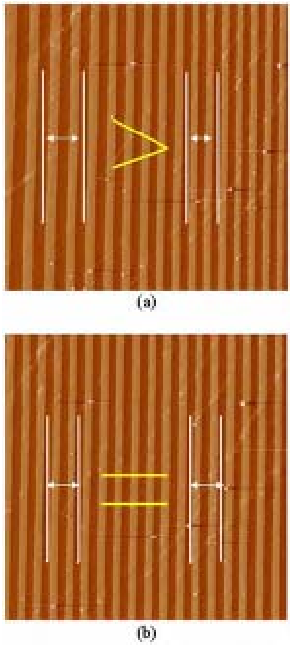

Fig. 8. Experimental results of the scanning over a periodic calibration grating. (a) Without hysteresis correction; (b) With hysteresis correction.

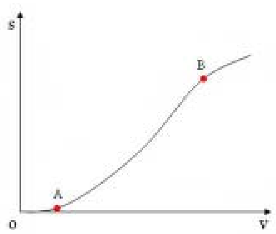

Fig. 9. The actual ascending curve of hysteresis

that the scanning performance of the AFM system has been improved greatly. The developed control and correction method can be extended to other applications as well, such as nanomanipulation, nanoassembly and machine vision process in future.

Here, it is necessary to mention that AFM piezo-scanner is not always working in full scale mode, which means that the hysteresis model is not constant. Despite so many problems, the biggest hard nut which is eager to be cracked in nano technology employing AFM is its lacking of real-time force feedback and visual feedback during manipulation, since the ultimate object of nano technology is that we can manufacture some functional devices or systems at the nano scale even atomic scale.

In order to suit applications with rigorous high precision and high efficiency requirements, the performance of the piezoelectric scanner, cantilever and probe system, mathematic modeling strategy, and the control algorithms should be improved entirely. Such efforts will be conducted in our further research work towards practical micro/nano manipulation task.

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