Аналізується нестаціонарне температурне поле у мембрані тензорезистивного сенсора тиску при термоударі. Показано, що внаслідок такого термовпливу мембрана може зазнати термопрогину і навіть термоколивань, що має суттєвий вплив на температурну похибку сенсора. Запропоновані шляхи зменшення термопрогину мембрани при нестаціонарному термовпливі і, таким чином, спосіб зменшення температурної похибки сенсора

Ключові слова: мембрана, термопрогин, сенсор тиску, нестаціонарна температура, точність вимірювання

Анализируется нестационарное температурное поле в мембране тензорезистивного датчика давления при термоударе. Показано, что в результате такого термовлияния мембрана может получить термопрогиб и даже термоколебания, что имеет существенное влияние на температурную погрешность датчика. Предложены пути уменьшения термопрогиба мембраны при нестационарном термовлиянии и, таким образом, способ уменьшения температурной погрешности датчика

Ключевые слова: мембрана, термопрогиб, датчик давления, нестационарная температура, точность измерения

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EFECT OF THE MEMBRANE THERMODEFLECTION ON THE ACCURACY OF A TENSORESISTIVE PRESSURE SENSOR

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1. Introduction

In strategic industries (aerospace technology, military equipment, testing complexes, research, etc.), various technical systems require the most precise sensors of physical magnitudes, in particular pressure sensors [1–5].

Among the large fleet of pressure sensors that are in use, a leading place is taken by tensoresistive sensors, which is predetermined by fundamental advantages [2, 3, 5].

One of the key requirements that the modern highly technological systems put forward to pressure sensors is the capability to perform measurements under conditions of fast-changing non-stationary temperature impacts.

In this case, it is required that the temperature error is within the class of accuracy. This is why an analysis of the reasons that lead to the occurrence of error in a a sensor is a task with absolutely relevance [2, 5].

2. Literature review and problem statement

Paper [6] examines a problem of the effect of nonstationary temperature on the accuracy of tensoresistive sensors. However, this worknot does not consider the phenomenon of a thermodeflection as a factor of influence on the sensor error.

One of the ways to minimize the impact of nonstationary temperature on tensoresistive pressure sensors is proposed in [7]. The article proposes applying additional screening elements in the form of thermal-protective films. In general, this method, while reducing the rate of thermal impact, yields a positive effect, however, it does not fundamentally eliminate thermal stresses and thermal deformations of the sensor membranes due to the effect of temperature. This is especially true for the thermodeflections of membranes as the immanent phenomena during thermal effect.

In order to solve the problem of pressure measurement in a hard environment, a tensoresistive pressure sensor was designed that can be used at high temperatures (above 200 °C) and is capable of enduring an instantenous impact of ultra-high temperature [8]. Such properties are based on the use of special technology for the formation of tensoresistive structure and specially designed mechanical construction of the sensor. However, the paper does not consider a possibility of applying the sensor for measurement under conditions of nonstationary temperature and does not solve the problem of accuracy at that. In particular, the problem of the membrane thermodeflection.

Article [9] analyzes thermal stresses in a pressure sensor. In particular, the author considered a problem of thermal stresses, which occurred as a result of thermal mismatch between the sensing element and the structure where it was located. As a result, there may occur a thermodeflection of the sensor membrane. However, this does not apply to the thermodeflection that occurs because of the direct effect of nonstationary temperature on the element.

The system of temperature compensation for pressure sensors is outlined in [10]. This system employs a high-precision temperature sensor and a digital circuit to implement temperature compensation. This method makes it possible to significantly influence the accuracy of pressure measurement under conditions of thermal effect, but is totally ineffective when it is necessary to compensate for the implications of nonstationary thermal effect.

Paper [11] reported a research into temperature compensation during measurement of pressure. It is proposed to use on the sensor membrane the tensoresistors, which form two measurement circuits. One circuit measures the deformation of sensor membrane due to the joint action of temperature and pressure, while another one – only due to temperature. The thermal compensation of measuring signal takes place by the difference in signals from these circuits. However, it is unclear how tensoresistors "tell" thermal deformation from the joint deformation due to pressure and temperature. In addition, the application of an additional measuring circuit requires further coordination of signals from these circuits, individual calibration of each sensor, which in general can greatly affect the accuracy. That is why it appears relevant to study the impact of various phenomena on the accuracy of pressure sensor, which are initiatiated by the temperature of measuting environment, in order to compensate for these phenomena at the structural level, without employing additional measuring circuits.

A method of thermocompensation, described in [12], utilizes new possibilities of semiconductor technologies and implies using additional polysilicon resistors with a negative coefficient of resistance (TCR). However, the results of this study cannot be applied to eliminate the implications of effect of nonstationary temperature on the sensor, especially to compensate for the effect of membrane thermodeflection.

We shall note that the problems of temperature stresses in the elements and structures were addressed in fundamental studies [13, 14]. These papers tackled a series of problems, which in one way or another could be applied in the consideration of tasks related to a temperature error of sensors. However, the problem of a temperature error of tensoresistive sensors under conditions of transient and non-stationary temperature impact has remained unresolved in terms of today's requirements.

3. Research goal and objectives

The goal of present work is to evaluate the impact of a membrane thermodeflection on temperature error of a tensoresistive pressure sensor when measuring under conditions of nonstationary temperature.

To accomplish the goal, the following tasks have been set:

– to analyze the character of temperature field in the sensor membrane during nonstationary thermal effect and to identify its features;

– to establish a relation between the features of temperature field in the membrane and its thermodeflection;

– to assess the degree of impact of thermodeflection on a temperature error of tensoresistive pressure sensor when measuring under conditions of nonstationary temperature;

– to develop recommendations for eliminating the given impact based on the research conducted.

4. Analysis of the membrane temperature field

Modern design practice of tensoresistive pressure sensors is characterized by certain trends regarding a fundamental solution to the design of the instrument [4–9]. Such trends are predetermined by physical-technological aspects and features of the utilized construction materials.

Thus, the structure of a tensoresistive pressure sensor consists of a membrane in the form of a circular plate, which is rigidly fixed in a massive casing, and tensoresistors, which are placed on the membrane (Fig. 1).

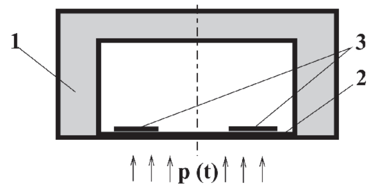

Fig. 1. Structural diagram of a typical tensoresistive pressure sensor: 1 – casing, 2 – membrane, 3 – tensoresistors, $p(t)$ is the measured pressure

When measuring pressure under conditions of a nonstationary change in the medium temperature, structural elements of the sensor undergo quite complex thermomechanical processes. One of such specific processes is a thermodeflection of membrane, which is caused by a non-uniform temperature field in it [14].

In order to implement the set goal, we shall analyze the dynamics of temperature field $T(r, z, t)$ in the membrane under boundary conditions typical for sensor operation. That is, there occurs a convective heat exchange in the contact plane of the membrane with the measurement environment at nonstationary temperature $T(t)$ (Fig. 2).

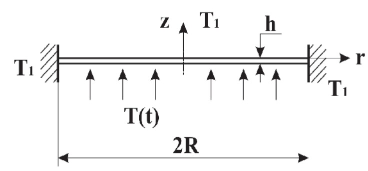

Fig. 2. Diagram of heat exchange on the membrane surfaces: R and h – radius and thickness of the membrane; T – temperature of the medium in contact with the perimeter and inner membrane surface; $T(t)$ – temperature of the measuring environment; r and z – coordinates along the radius and by thickness of the membrane

In order to evaluate the effect of membrane thermodeflection on the accuracy of a tensoresistive sensor when measuring pressure in the environments with arbitrary and unpredictable nonstationarity, it is proposed to perform an analysis of thermoelastic processes at the largest thermal effect – a thermal shock. This technique will yield an assessment of the effect of temperature on the sensor "from the top", while at less severe thermal effects it would be overstated. However, given the complexity in the design of experimental equipment for the reproduction of a thermal effect that changes over time, the proposed technique is universal as it will provide the assessment of thermoelastic processes in the sensor elements at the largest thermal effect. In addition, there is experimental equipment to create thermal shocks [15–17].

In order to "strengthen" the effect of a thermal shock, we shall assume that the inner side of the membrane and the perimeter are in contact with media of constant temperature. Under actual conditions, both on the inside and on the perimeter of a membrane the media temperatures would change in proportion to the «warming up» of the entire sensor. That is why the nonuniformity of temperature field in the membrane will be smaller.

In this case, the membrane, which is a round plate with radius R, thickness h, made of isotropic material and has the following constants: K is the coefficient of thermal conductivity, κ is the specific heat capacity, $\chi=\frac{K}{\rho\cdot\kappa}$, is the coefficient of temperature conductivity, ρ is the membrane material density.

To determine a temperature field in the membrane, it is necessary to solve equation [18]

$$\frac{\partial^2 T(r,z,t)}{\partial r^2}+\frac{1}{r}\frac{\partial T(r,z,t)}{\partial r}+ +\frac{\partial^2 T(r,z,t)}{\partial z^2}-\frac{1}{\chi}\frac{\partial T(r,z,t)}{\partial t}=0, \quad (1)$$

under boundary and initial conditions

$$\left.\begin{aligned}&\frac{\partial T(r,z,t)}{\partial r}+l_3(T(r,z,t)-T_1)=0 && \text{at } r=R,\\ &\frac{\partial T(r,z,t)}{\partial z}-l_1(T(r,z,t)-T(t))=0 && \text{at } z=0,\\ &\frac{\partial T(r,z,t)}{\partial z}+l_2(T(r,z,t)-T_1)=0 && \text{at } z=h,\\ &T(r,z,t)=T_0=\text{const} && \text{at } t=0,\end{aligned}\right\} \quad (2)$$

where l_1, l_2, l_3 are the normalized heat exchange coefficients on the contact and inner surfaces and perimeter of the membrane; T_1 is the temperature of medium in contact with the perimeter and inner surface; T_0 is the initial temperature of the membrane, which is the same all over its body.

Solution (1) is the equations

$$T(r,z,t)=T_0+T_\partial(r,z,t)+T_y(r,z), \quad (3)$$

where

$$T_\partial(r,z,t)=-\frac{4\Delta T\cdot l_1\cdot l_3}{R}\times \times\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\phi_2(z,\beta_m)\cdot e^{-\chi(a_n^2+\beta_m^2)t}\cdot\beta_m}{(a_n^2+\beta_m^2)\cdot\phi_3(\beta_m)}\cdot\phi_1(r,a_n), \quad (4)$$

dynamic, or a transitional component,

$$T_y(r,z)=-\frac{2\Delta T\cdot l_1\cdot l_3}{R}\times \times\sum_{n=1}^{\infty}\frac{a_n ch(a_n(h-z))+l_2 sh(a_n(h-z))}{(l_1+l_2)a_n ch(a_n h)+(l_1 l_2+a_n^2)sh(a_n h)}\phi_1(r,a_n), \quad (5)$$

an established component.

In these equations: ΔT is the amplitude of the thermal shock, and

$$\phi_1(a_n,r)=\frac{J_0(a_n r)}{(l_3^2+a_n^2)J_0(a_n R)}, \quad (6)$$

$$\phi_2(\beta_m,z)=\beta_m\cos\beta_m(h-z)+l_2\sin\beta_m(h-z), \quad (7)$$

$$\phi_3(a_n,r)=\beta_m\left[2+h(l_1+l_2)\right]\sin\beta_m h- -\left[h\left(l_1\cdot l_2-\beta_m^2\right)+l_1+l_2\right]\cos\beta_m h, \quad (8)$$

where a_n are the roots of equation

$$a_n\cdot J_1(a_n R)-h_2\cdot J_0(a_n R)=0;$$

$J_0(a_n R)$ and $J_1(a_n R)$ are the Bessel functions; β_m are the roots of equation

$$ctg\beta_m h=\frac{1}{l_1+l_2}\left(\beta_m-\frac{l_1\cdot l_2}{\beta_m}\right).$$

Equation (3) describes thermal field in the membrane during thermal shock.

In order to evaluate the "weight" of membrane thermodeflection $w(r, t)$, we shall solve a differential equation that describes its deflection during a nonstationary thermal effect [14]

$$c^4\Delta^2 w(r,t)+\frac{\partial^2 w(r,t)}{\partial t^2}+2\beta\frac{\partial w(r,t)}{\partial t}=\frac{p_T(t)}{\gamma}. \quad (9)$$

Under boundary and initial conditions

$$w(r,t)=\frac{\partial w(r,t)}{\partial r}=0 \text{ at } r=R,$$

$$w(r,t)=\frac{\partial w(r,t)}{\partial t}=0 \text{ at } t=0,$$

where

$$c^4=\frac{D}{\gamma}=\frac{Eh^3}{12(1-\nu^2)\rho h},\quad D=\frac{Eh^3}{12(1-\nu^2)},$$

$\gamma=\rho h$, E is the modulus of elasticity, ν is the Poisson coefficient, $\nabla=\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}$, ρ is the membrane material density, β is the damping coefficient of membrane oscillations,

$$p_T(t)=-\frac{\nabla M_T(r,t)}{1-\nu},$$

the bending moment $M_T(r, t)$, predetermined by a variable-along-the-radius difference in temperatures by thickness of the membrane is

$$M_T(r,t)=\frac{(1+\nu)D\lambda}{h}\left[T(r,h,t)-T(r,0,t)\right], \quad (10)$$

where λ is the coefficient of linear thermal expansion.

As is known [18], solution (9) will be written in the form

$$w(t,r)=\sum_{n=0}^{\infty}\phi_n(k_n r)\times \times\frac{\zeta_n}{\eta_n}\int_0^t p_T(\tau)\cdot e^{-\beta(t-\tau)}\cdot\sin(\eta_n(t-\tau))d\tau, \quad (11)$$

where

$$\phi_n(k_n r)=J_0(k_n r)\cdot I_0(\mu_n)-J_0(\mu_n)\cdot I_0(k_n r)$$

are the eigenfunctions of the corresponding boundary problem, $J_0(\mu_n)$, $I_0(\mu_n)$, $J_1(\mu_n)$, $I_1(\mu_n)$, $J_0(k_n r)$, $I_0(k_n r)$ are the Bessel functions,

$$\zeta_n = \frac{J_1(\mu_n)\cdot I_0(\mu_n) - J_0(\mu_n)\cdot I_1(\mu_n)}{\mu_n \cdot J_0^{\,2}(\mu_n)\cdot I_0^{\,2}(\mu_n)},$$

$\mu_n = k_n \cdot R$ are the eigenvalues of the corresponding boundary problem

$$\eta_n = \sqrt{\xi_n^2 - \beta^2},$$

$$\xi_n^2 = c^4 \cdot \frac{\mu_n^4}{R^4}.$$

Taking into account expression (11), a deflection in the center of the membrane will equal to

$$w_0 = w_0(t, T^0)\big|_{r=0} =$$
$$= \sum_{n=0}^{\infty} \phi_n(0) \cdot \frac{\zeta_n}{\eta_n} \int_0^t p_T(\tau) \cdot e^{-\beta(t-\tau)} \cdot \sin(\eta_n (t-\tau)) d\tau, \qquad (12)$$

where $\phi_n(0) = I_0(\mu_n) - J_0(\mu_n)$.

Expression (11) allows us to simulate the dynamics of a sensor membrane thermodeflection depending on the temperature field in it and at its different parameters. Thus, for example, during thermal shock with an amplitude of ΔT=400 °C and membrane parameters: R=0.005 m and h=0,00025 m, the thermodeflection of its center is 5.5 μm (Fig. 3), which for many types of sensors is quite significant.

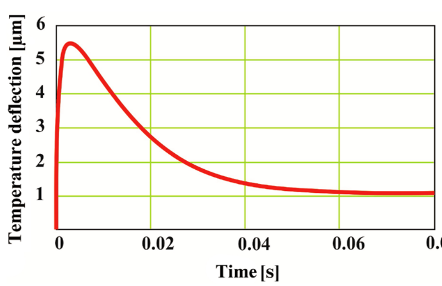

Fig. 3. Dynamics of thermodeflection of the center of membrane during thermal shock

In order to evaluate the effect of membrane thermodeflection on the sensor error, we shall compute the values of deformations that occur in the membrane due to thermodeflection.

As is known [19], relative radial and tangential deformations on the membrane surface (Fig. 4) during deflection of its centre $w_0(t)$ are

$$\varepsilon_r = \frac{2 w_0(t)\cdot h}{R^2}\left(3\frac{r^2}{R^2} - 1\right), \qquad (13)$$

$$\varepsilon_\phi = \frac{2 w_0(t)\cdot h}{R^2}\left(\frac{r^2}{R^2} - 1\right). \qquad (14)$$

For example, for a membrane with R=0.005 m and h=0,00025 m, Fig. 5 shows a relative radial deformation $\varepsilon_r(t)$, calculated by (13), during thermodeflection due to a thermal shock ΔT 400 °C.

This example demonstrates that although the maximal value of thermodeflection (Fig. 5) was only 5.5 μm, but the maximal value of radial deformation of the membrane amounted to 7.8×10^{-5}. If for the tensoresistors that are typically used in sensors [20, 21], the working level of deformation is ~1×10^{-4}, then deformations due to thermodeflection will have a significant impact on the result of measurement.

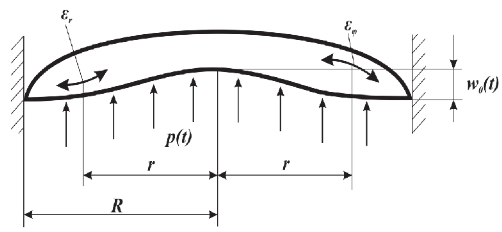

Fig. 4. Relative deformations on the membrane surface during deflection: R — radius of the membrane; $p(t)$ — measured pressure; r — coordinate along radius of the membrane; ε_r and εφ — relative radial and tangential deformation on the membrane surface during deflection $w_0(t)$ of its center

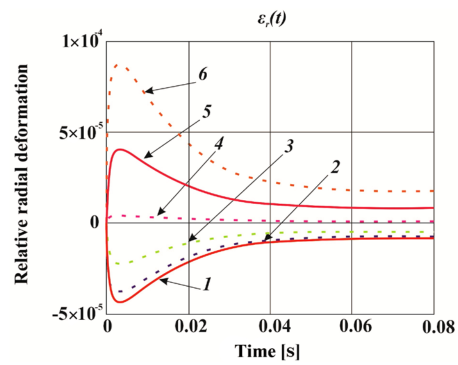

Fig. 5. Dynamics of relative radial deformation in different points of the membrane due to its thermodeflection: 1 — at r=0 mm; 2 — at r=1 mm; 3 — at r=2 mm; 4 — at r=3 mm; 5 — at r=4 mm; 6 — at r=5 mm

However, when modeling a nonstationary thermal field in the diaphragm at its different geometrical parameters and heat exchange coefficient on the perimeter, it was found that even at temperature gradient by thickness (Fig. 6), the temperature gradient along the radius may exist (Fig. 7), and can be absent (Fig. 8).

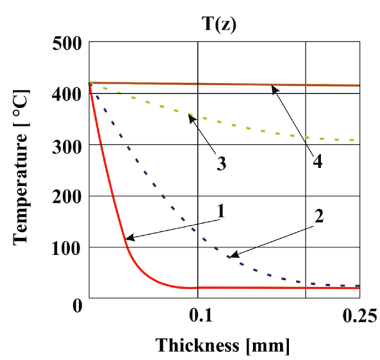

Fig. 6. Temperature gradient by thickness of the diaphragm over discrete time moments (in the center of the membrane (r=0 mm)): 1 — at t=1 ms; 2 — at t=10 ms; 3 — at t=0.1 s; 4 — at t=10 s

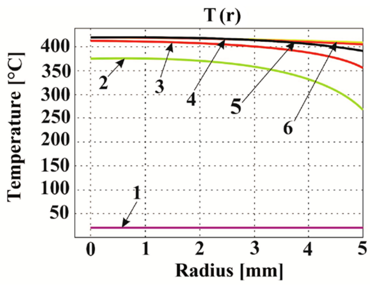

Fig. 7. Temperature gradient along radius of the diaphragm over discrete time moments: 1 – at t=0.1 ms; 2 – at t=0.1 s; 3 – at t=1 s; 4 – at t=3 s; 5 – at t=6 s; 6– at t=10 s

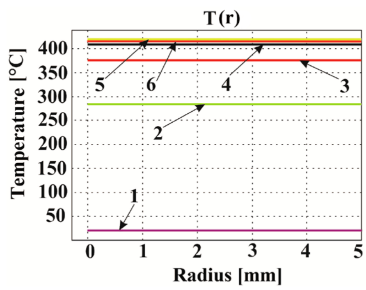

Fig. 8. Dynamics of temperature along radius of the diaphragm over discrete time moments: 1 – at t=0.1 ms; 2 – at t=0.01 s; 3 – at t=0.1 s; 4 – at t=1 s; 5 – at t=6 s; 6 – at t=10 s

In the case of absence of the gradient, we receive from formula (11)

$$\nabla M_T(r,t)=0, \tag{15}$$

which is why

$$p_T(t)=-\frac{\nabla M_T(r,t)}{1-\nu}=0$$

and thermodeflection

$$w(r,t)=\sum_{n=0}^{\infty}\phi_n(k_n r)\times$$

$$\times\frac{\zeta_n}{\eta_n}\int_0^t p_T(\tau)\cdot e^{-\beta(t-\tau)}\cdot\sin(\eta_n(t-\tau))d\tau=0.$$

That is, by minimizing the temperature gradient along radius of the membrane, it is possible to obtain minimization of the thermodeflection.

5. Discussion of results of the study of effect of membrane thermodeflection on the accuracy of a tensoresistive pressure sensor

The obtained results show that thermodeflection significantly increases temperature error of the pressure sensor when measuring under conditions of nonstationary temperature of the medium, which that significantly affect the accuracy of the pressure sensor. Under a stationary thermal effect, by using different methods of thermocompensation, it is possible quite effectively to correct a temperature error of the sensor. However, at a nonstationary thermal effect, it is the existence of thermodeflection that renders these methods ineffective, as it is not possible to recognize deflection of the membrane due to pressure from that due to temperature. Therefore, it is required to minimize and ideally eliminate the thermodeflection. This can be achieved by minimizing the gradient of temperature field along radius of the membrane by the thermal isolation of its perimeter, or through a special selection of parameters and materials of the casing of sensor and membrane that possess the according thermal conductivities.

The analytical dependences derived in the course of present research allow us to calculate possible thermodeflection of membrane of the pressure sensor based on actual conditions of operation. In addition, by employing a condition of the thermodeflection minimum, it is possible to select appropriate physical-mechanical parameters for the sensor elements.

Given that the analysis of temperature field in the membrane was performed during thermal shock as the most severe thermal effect, then for other forms of thermal effect results will be somewhat «overstated». That is, in reality, the thermodeflection and its effect on the temperature error may appear smaller. However, the use of thermal shock conditions simplifies the calculation, since there is no need to determine coefficients of heat exchange between the medium and the membrane, which is a challenging task.

In addition, the results obtained demonstrate that at oscilating character of the thermal effect, there may occur the thermal oscillations of the membrane. All this leads to the formation of a rather complicated character of temperature error of the sensor and unpredictable accuracy in the measurement of pressure.

The results received will be particularly valuable when designing pressure sensors for automated control systems, where a rapid correction of additional errors in measurement is required.

In further research, it would be appropriate to verify theoretically and experimentally possible methods for eliminating thermodeflection, as well as to establish the influence of the character of thermal effect and of the main membrane parameters on the amplitude and character of thermodeflection.

6. Conclusions

1. We derived analytical dependences that describe a nonstationary temperature field in the membrane of a tensoresistive pressure sensor, which allows performing an analysis of the character of the field, as well as discovering its features depending on specific parameters of the membrane.

2. It is found that the temperature field of membrane, despite a change in its thickness, may or may not have a gradient along the radius. The existence of a gradient along radius of the membrane results in its thermodeflection, while there is no thermodeflection in the absence of the gradient.

3. It is demonstrated that during a fast-changing thermal effect the thermodeflection value significantly affects the accuracy of the sensor, as it can be comparable to the working deformations of the membrane and, thereby, create a 100 % additional error.

4. To eliminate the negative influence of thermodeflection, it is necessary to minimize the gradient of temperature field along radius of the membrane by the thermal isolation of its perimeter, or by a special selection of parameters and materials of the casing of the sensor and the membrane.

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