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CALIBRATION OF THE TORSION FORCE MEASUREMENT SYSTEM FOR THE LORENTZ FORCE VELOCIETRY APPLICATION

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ABSTRACT

The in this paper described torsion force measurement system contributes to the Lorentz force velocimetry application, where the horizontal force in combination with dead load of 1 kg is measured. The theoretically calculated stiffness of the system is 0.5 N/m, undamped nature frequency is 0.06 Hz and it is expected to achieve the force resolution of 0.5 nN. Initially the electrical voltage as the output signal of the photoelectrical position sensor is converted into angle with an autocollimator system. Then the output signal of the position sensor is calibrated into force with the help of a known tilt force generated by tilt angle and a normal mass piece, the convert factors for the two positon sensors are 37.1038 µN/V and 38.7247 µN/V. A standard deviation of 5.5 nN over one hour has also been achieved and the linear working range of the system is nearly ± 40 µN.

Index Terms - Torsion balance, horizontal force measurement, high dead load

1. INTRODUCTION

In this paper we describe a torsion force measurement system (short: TFMS) and discuss several recent experiments which have been made to investigate its performance. The TFMS is developed as a part of the Lorentz force velocimetry (short: LFV) project which has been introduced as a contactless method to measure the flow velocity and is suited for opaqueness or chemical aggressive liquids [1]. The principle of LFV has been introduced in several works such as [1-3]. The conducting fluid flows with the velocity v in the channel, which is located in the magnetic field $\vec{B}$ generated by a permanent magnet. Then the Lorentz force f_L will act on the fluids to break down the flow motion. According to the Newton's third law a force f_L' with the equal magnitude will act on the magnet in the opposite direction and this force will be measured by the force measurement system. The force f_L' is proportional to the velocity v, the electrical conductivity σ and the second order of the magnetic field $\vec{B}$. In the case of known σ and $\vec{B}$, and the measured force f_L', the velocity v can be calculated; similarly the electrical conductivity of the fluid could also be measured if the velocity v is a known value.

In some occasions the LFV works for low conducting flows such as glass melts whose conductivity can be down to 10^{-6} S/m and the generated Lorentz force is in the range of Micronewton and below; meanwhile the force measurement system has to carry the Halbach magnet which is about 1 kg [4]. Therefore the challenge is to improve the force resolution in combination with the high dead load. In previous work of C. Diethold and S. Vasilyan the system of single/double electromagnetic force compensated (short: EMFC) weighing cell/ cells made by Sartorius was used in suspended position to measure the force in horizontal direction [2, 3]. With the differential force measurement method a force resolution of about 20 nN was achieved and enabled the flow rate measurement for conductivity down to 0.06 S/m [3, 5]. With the aim to improve the force measurement resolution the tilt sensitivity of the EFMC weighing cell has been checked in previous work and a method by adding dead load on the weighing cell to minimize the influence generated by tilt sensitivity has been found [6]. In the LFV application, concerning the 1 kg dead load of the magnet, it is not desirable to apply the mass piece of this order on the precise weighing cell. Therefore a torsion force measurement system has been designed to overcome the tilt sensitivity problem. In the following sections the structure of the system and some recent experimental results are presented.

2. TORSION FORCE MEASUREMENT SYSTEM

The mechanical construction of the experimental setup TFMS is shown in figure 1. Principle is to convert the force exerted on the system into a deflection which is able to be measured by positon sensor. When the force f_L' is acting on the magnet ②, the with magnet together screwed wheel ④ is set into rotational motion and the movement is being detected by the photoelectrical position sensor ③. Knowing the stiffness of the system the measured displacement can be calculated into the force values. An advantage of the system is that the dummy weight ⑤ applied on the opposite side of the arm has the same weight as the magnet; meanwhile the arm length L_1 is equal to L_2 (see figure 1), which in ideal case sets the center of the gravity of the system in the rotation axis and fulfill the requirement for an insensitive system against inclination. In other words the inclination of the system will cause no effect on the measurement results. The second advantage is the use of the commercial flexible bearing ⑦ that provides a low torsional spring constant, 1.17e^{-2} N·m/rad [7], which means that the system is more sensitive against low forces.

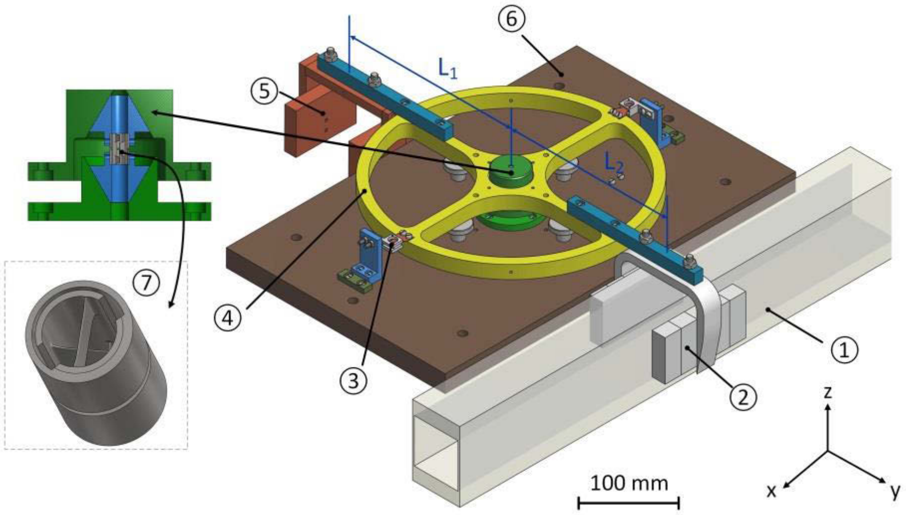

Figure 1: Mechanical construction of TMFS
(①- channel, ②- Halbach magnet, ③- position sensor, ④- wheel, ⑤- dummy,
⑥- baseplate, ⑦- flexible bearing)

In the LFV application the force f_L' exerts on the magnet, and then the stiffness of the TFMS C_t can be calculated as approximately 0.5 N/m with equation 1:

$$C_t = \frac{C_r}{L_2 \cdot R} \qquad (1)$$

C_t – stiffness of the TFMS
C_r – torsional spring constant of the flexible bearing: 1.17e^{-2} N·m/rad
L_2 – arm length from magnet to centre of the TFMS: 180 mm
R – radius from position sensor to the centre of the TFMS: 135 mm

As the position sensor provides the resolution of 1 nm the expected force measurement resolution of the TFMS is 0.5 nN. By this system the force measurements are expected to be greatly improved.

3. TRANSFER THE SCALE OF POSITION SENSOR INTO ROTATION ANGLE

The photoelectrical position sensor (③ in figure 1) is consisted of a high power LED, a differential photodiode which are both fixed on the baseplate ⑥ and an aperture screwed on the wheel. The position change of the aperture indicates the movement of the wheel and leads to the change of the received light on the photodiode, from which the electrical voltage as the output signal is measured. To measure the position the original output signal should be converted into a distance change in µm or rotation angle in radiant. In this respect the factor K_1 in the equation 2 should be determined:

$$S = K_1 \cdot U \text{ or } \theta = K_1 \cdot U \qquad (2)$$

S – displacement (in µm)
θ – rotation angle (in radiant)
U – output voltage (in V)

As the flow diagram in figure 2 shows the converting process has been carried out with the help of an autocollimator system which is able to detect the rotation angle of the wheel. The TFMS is located on a precise tilt stage which was also developed in TU Ilmenau and in this experiment can be controlled to generate different tilt angles α around x axis step by step [8]. A mass piece m_1 of 10 g of OIML E2 class is placed on the wheel (in figure 3 with blue marked), therefore a tilt force of $f_t = m_1 \cdot g \cdot \sin \alpha$ is generated along y axis and drives the wheel into rotation motion. This motion is detected at the same time by the auto collimator system and by the photoelectrical position senor. Thus the output signal from the position sensor as electrical voltage can be converted into position signal as rotation angle.

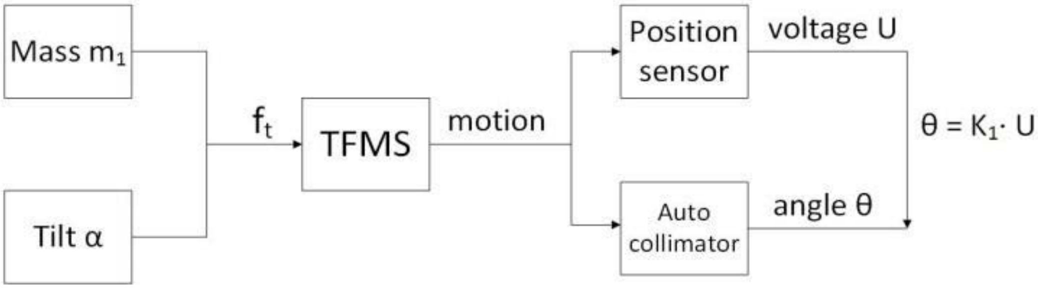

Figure 2: Flow diagram of the transfer process

The experiment has been repeated 5 times and the results are presented in figure 4, where the horizontal scale indicates the measured angle by the autocollimator system while the vertical scale shows the output voltage from the two position sensors. The linear fitting is applied on the measured data. From the measurement results is to be seen that the linear working range of the position sensor is approximately ± 1 V, the calculated convert factors of the two position sensors are 0.4103 mrad/V and 0.4152 mrad/V.

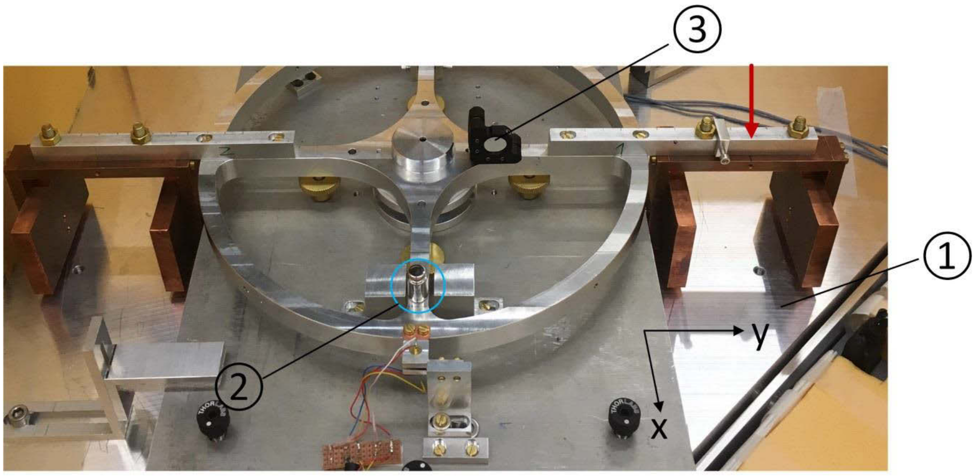

Figure 3: Experimental setup for the output transfer of the position sensor
(1- tilt stage; 2- mass piece to generate tilt force; 3- mirror)

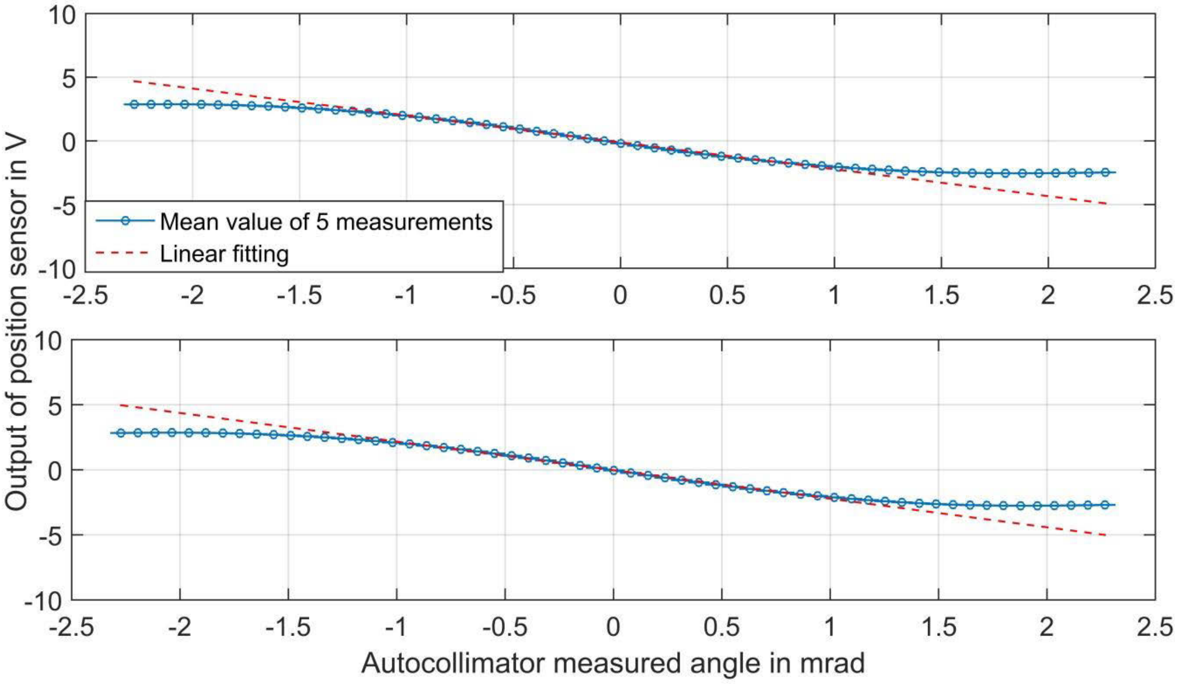

Figure 4: Experimental results for the output transfer of the position sensor
(top: position sensor 1; bottom: position sensor 2)

The difference between the two factors can be a result of the different distance from the two apertures to the center of the system caused by manufacturing or assembling. Thus the output signal of the two position sensors haven been adjusted from electrical voltage into rotation angle.

4. FORCE CALIBRATION OF THE TFMS

In the section 3 a mass piece has been used to generate a tilt force on the TFMS in order to drive the system to rotate. Here in this section this method is used again to generate a known force in order to calibrate the output signal from position sensor directly into force. Although the TFMS has been introduced as a theoretically insensitive setup against influence of inclination, the tilt sensitivity could still remain as a result of misalignment during assembling or manufacturing deviations. Therefore before applying force on the TMFS the tilt sensitivity has been tested and minimized into a limit of 7.4 nrad/µrad which indicates the smallest angle change can be detected by the position sensor. After that the mass piece of 1 g, 2 g and 4 g (combination of two 2 g) from OIML class of E2 weight set have been located separately on a specific place of the TFMS where later the Lorentz force will exert (see figure 3 with red arrow marked). The tilt angles are generated by the tilt stage around y from -2 mrad to + 2 mrad in 40 steps.

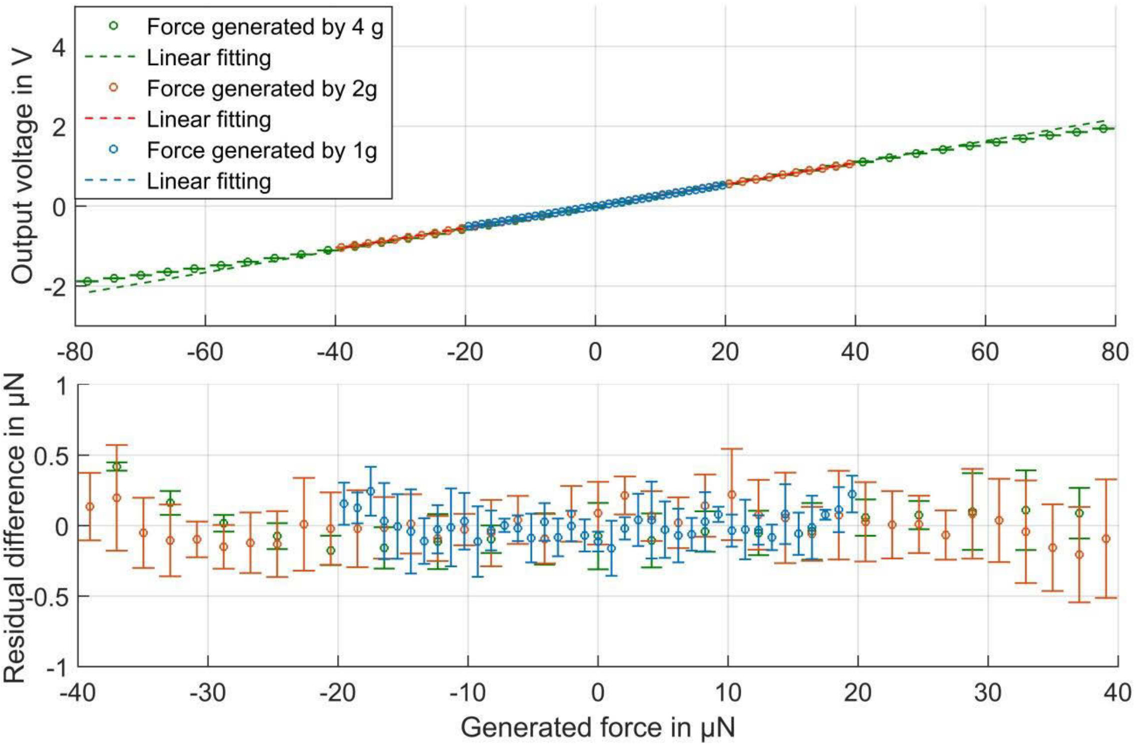

Figure 5: Force calibration results

The measurement results are shown in figure 5 and the force calibration factors with deferent mass pieces for the both position sensors are shown in Table 1. The uncertainty in the experimental results with each mass piece is calculated from 10 repeated measurements with a confidence interval of 95%. With different mass pieces the reproducibility of 0.5460 µN/V and 0.7836 µN/V has been achieved separately for the two position sensors. In section 3 the linear working range of the position sensor is indicated as ± 1 V, namely approximately ± 40 µN when multiplied by the factor K_f.

Force factor K_f (µN/V)	Position sensor 1	Position sensor 2
1 g (blue)	37.8258 ± 0.2015	39.7584 ± 0.2202
2 g (red)	36.9801 ± 0.0799	38.5538 ± 0.0786
4 g (green)	36.5056 ± 0.1176	37.8620 ± 0.1247
Mean Value	37.1038	38.7247
Reproducibility	0.5460	0.7836

Table 1: Experiment result: force transfer factors

With the measurement results in section 3 and 4 the rotational stiffness of the system can also be determined when the K_f divided by K_1 and it is about 0.09 N/rad.

5. LONG-TERM STABILITY

As the output of the TFMS has been calibrated into force the static characteristic would be tested in this section. At first the free oscillation of the wheel has been observed for over 22 hours to test the long-term stability of the system as shown in figure 6. After the factor K_{f1} and K_{f2} have been determined in previous section the output signal has been described into force. A floating mean value filter with the length of N = 1200 which corresponds to a filter time of one minute (sampling frequency of the measurement is 20 Hz) was applied to the measured raw signal. The highlight in figure 6 shows the signal in a zone of one hour, the standard deviation in this period is 22.7 µN and after filtered is 5.5 nN, here also shows that the output force is not perfect stable at zero positon when no external force acting on the system, a drift is obvious. During the long-term measurement the temperature was also recorded by a PT-100 temperature sensor, see bottom right corner of figure 6. It can be deduced that the drift in force signal corresponds with the temperature trend. The reason of the temperature dependency is that the photoelectrical position sensor can also be temperature depended. Figure 7 shows the Fourier transformation of the measurement, which indicates the character of the TFMS in frequency domain. The undamped nature frequency of the system is 0.06 Hz, which agrees with calculation. The lower nature frequency is resulted from the high dead load and the low stiffness of the system. The figure 6 also indicates that it takes about almost 10 hours until the system reaches a stable situation.

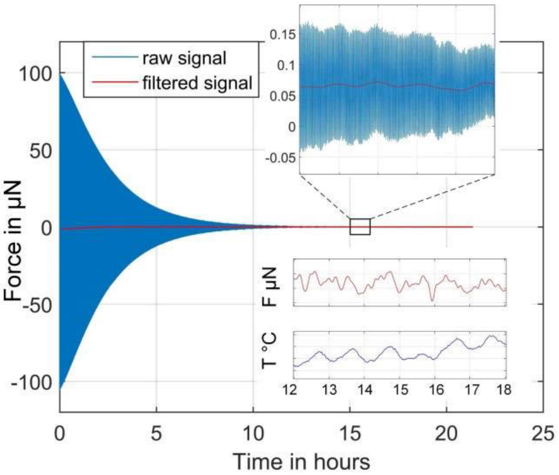

Figure 6: Long-term free oscillation of the system

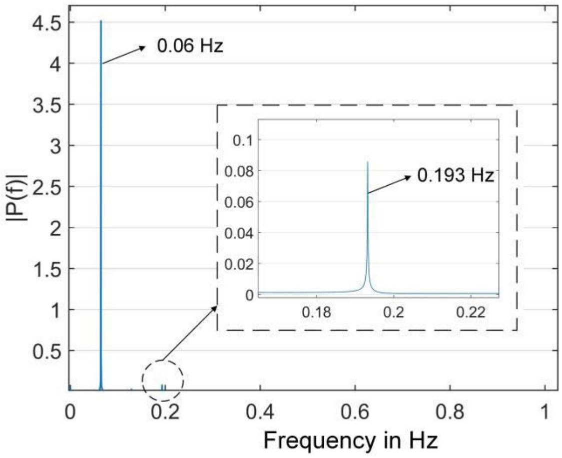

Figure 7: Fourier transformation of force signal

Besides the natural frequency another component by 0.193 Hz with much lower amplitude can be seen in figure 7. It may be resulted by an unwanted vibration of the wheel around x or y axis. Compared to the rotation motion as the measured signal this vibration can be neglected. Damper can also be assembled to the system in order to inhibit the undesirable vibration.

In this experiment a standard deviation of 5.5 nN was achieved over 1 hour and a drift of the measured signal could also be seen. This drift is correspond to the temperature change and supposed to be caused by the temperature dependency of the positon sensor.

6. CONCLUSITON AND OUTLOOK

For meeting the requirements of the force measurements in the LFV application, a force measurement system based on the torsion balance is described in this paper. This system is introduced as a theoretically insensitive system against inclination influences. Initially the photoelectrical position sensor has been adjusted by converting the output signal from electrical voltage into rotation angle with the help of the precise tilt stage. The convert factors of the two position sensors are 0.4103 mrad/V and 0.4152 mrad/V. After that a known force generated by a known mass piece acted on the system and in this way the output can be calculated into force directly. The two force factors are $K_{f1} = 37.1038\ \mu\mathrm{N/V}$ and $K_{f2} = 38.7247\ \mu\mathrm{N/V}$. The stiffness of the TMFS about 0.09 N/rad could also be calculated with the measurement results and the force measurement resolution is expected to be 0.5 nN. In the long-term measurement the standard deviation of 5.5 nN over 1 hour has been achieved.

Further, additional experiments are planned to be carried out on the TFMS. The force will be calibrated with force generator as voice coil actuator or capacitive force generator. A control loop to balance the motion to a zero position will be developed. The system is expected to measure forces with down to 1 nN resolution. Therefore the main work and test measurements in future would concern the resolution and accuracy improvements of the TFMS.

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REFERENCES

[1] A. Thess, E. Votyakov and Y. Kolesnikov, “Lorentz force velocimetry” Phys. Rev. Lett. 96 164501

[2] C. Diethold, S. Vasilyan, T. Fröhlich, “Lorentz force velocimetry using electromagnetic force compensated load cells,” IMEKO 2014

[3] S. Vasiliyan, T. Fröhlich, “Direct Lorentz force compensation flowmeter for electrolytes,” Applied Physics Letters 105, 223510 (2014); doi: 10.1063/1.4903235

[4] M. Werner: “Design, Optimierung, Realisierung und Test von passiven Magnetsystemen für die Lorentzkraftanemometrie an Elektrolyten”, Dissertation, Technische Universität Ilmenau, 2012

[5] S. Vasilyan, “High Precision Force Measurements in Horizontal Direction in Combination with High Dead Loads: Non-Contact Flowmeter for Low Conducting Electrolytes”, Dissertation 2016

[6] N. Yan, S. Vasilyan, M. Kühnel and T. Fröhlich, “Investigation to the tilt sensitivity of the Lorentz force system for the flow rate measurement of low conducting fluids,” IMEKO 2017

[7] C-FLEX BEARING COMPANY, INC. https://c-flex.com/

[8] M. Rivero, M. Kühnel, “High precision dual axis tilt stage,” IWK *2014*

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