ANALYSIS ON OSCILLATING ACTUATOR FREQUENCY INFLUENCE TO THE FLUID FLOW CHARACTERIZATION FOR 2D CONTRACTILE WATER JET THRUSTER

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ABSTRACT

Contractile body is an alternative mechanism instead of rotating blade propeller to generate water jet for locomotion. The oscillating motion of the actuator at different frequencies varies the pressure and volume of the pressure chamber in time to draw in and jetting out the water at certain mass flow rate. The aim of this research was to analyze the influence of the actuating frequency on the fluid flow in the pressure chamber of the thruster during this inflation-deflation process. A 70mm x 70mm x 18mm (L x W x T) 2D water jet thruster was fabricated for this purpose. The contractile function was driven using two lateral pneumatic actuators where the fluid flow analysis was focused on the X-Y plane vector. Observation was carried out using video camera and Matlab image measurement technique to determine the volume of the flowing mass. The result demonstrated that greater actuating frequency decreases the fluid flow rate and the Reynolds number. This observations shows that the higher frequency would give higher mass flow rate during water jet generation.

Keywords: Oscillating actuator, Actuating frequency, Water jet thruster, Mass flow rate, Thrust force.

INTRODUCTION

Contractile water jet thruster (CWT) is an alternative propulsion method for underwater robot. CWT had been utilized either as main propulsion unit (Yeom et al. 2009; Barber et al. 2010) or underwater vehicle's direction guiding unit (Thomas et al. 2005). Basically, this CWT applies the pressurized water jet to accelerate its body for locomotion. Compared to motor driven rotary blade propeller, this CWT uses pressure chamber volume reduction to generate this pressurized water jet (Figure 1). The pressure chamber volume reduction or contraction occurred by applying an amount of force to certain parts of its body. During actuation, the actuator contracts the pressure chamber body to expel the water from the chamber via nozzle or orifice. Recurring contraction is required for continuous locomotion, thus exhibiting the function of actuating frequency. Though intensive research had been carried out to characterize the

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CWT mechanism, few detail studies were focus on the actuating frequency influence on the internal fluid flow of the CWT.
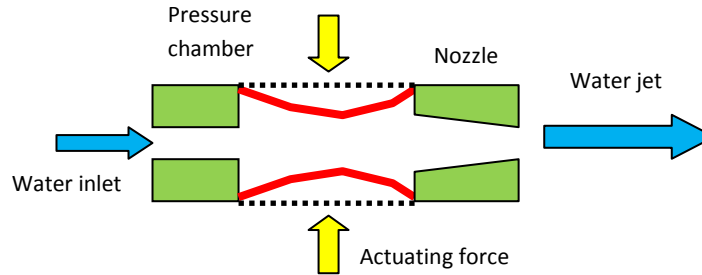

Figure 1. Fundamental concept of contractile water jet mechanism

A maximum mass flow rate at optimum velocity during the jetting period would create ultimate propulsion efficiency for a certain CWT specification. In the CWT context, the maximum mass flow rate could be only achieved by the right actuating frequency. Higher frequency would entrain less water and thus it would decrease the mass flow rate magnitude. Otherwise too low frequency reduces the velocity of the jetted fluid. In this research, the oscillating actuator frequency was varied atlow frequency and the fluid flow behaviour was observed during the inflation and deflation process. At this moment, the studied focus on the 2D fluid flow characterization. In real application, smart actuator will be used. However in this research, the smart actuator was substituted with pneumatic cylinder for easy control purpose. A 70mm x 70mm x 3mm (L x W x T) 2D water jet thruster was fabricated and attached to two pneumatic cylinders. Maximum static pressure for cylinder actuation was set at the compressor regulator to obtain the required actuating force. Oscillating motion and frequency of the actuators was controlled using Arduino UNO microcontroller. The fluid flow during inflation and contraction of the CWT was observed through the motion of the red colour, supplied at the inlet and nozzle using transfusion needle. In order to gain the fluid velocity, a 30 frame-per-second video camera was used to catch the motion of the red colour. The results shows that the increased actuating frequency decreases the volume flow rate and Re number.

RESEARCH OVERVIEW

Oscillating actuation frequency depends on the type of the actuator. Each of the potential actuator has its own character and hence must match the design optimization of the CWT for ultimate thrust force generation (Shaari et al. 2012). For instance, piezo based actuator has high actuating frequency which would be up to 8MHz (Tan et al. 2010) could form a small and compact CWT because of the properties of the piezo material. IPMC actuator which acts by bending mechanism has lower actuating frequency compared to the piezo actuator but larger bending radius allows more mass flow rate (Shahinpoor et al. 2005). Generally CWT has three stages of action during its operation which are the rest, inflation and deflation stage. These three stages mimic the nature of water jet locomotion aquatic animals such as squid, jellyfish and nautilus (Gladfelter, 1972; Bartol et al., 2001). The rest stage would be the initial condition or

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recovery stage where there is neither kinematic change of the body nor actuation occurred. The second stage is the inflation stage where the volume of the pressure chamber increase dramatically depends on the speed of the actuator (Figure 2a). Based on Boyle's Law, the lower pressure entrained surrounding water to fill in the cavity. The third stage is the deflation process where again the actuator contract the CWT body and pressure increment enforce the water out via a nozzle (Figure 2b).
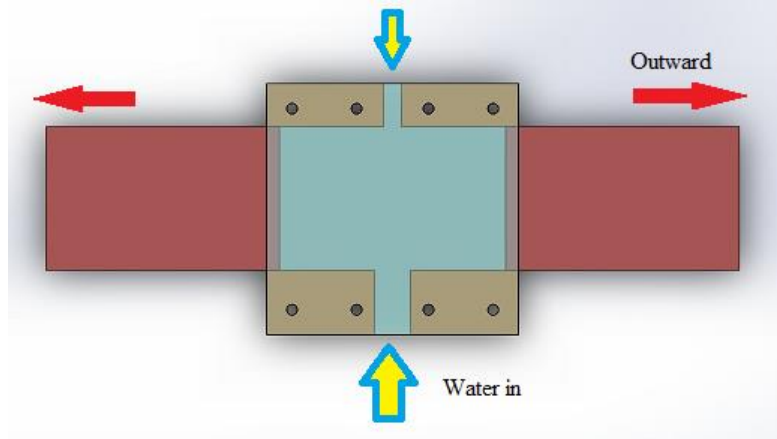
a) Inflation
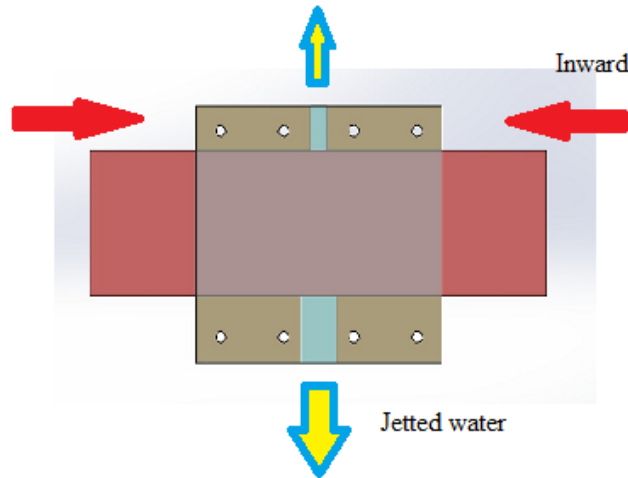
b) Deflation

Figure 2. Inflation and deflation of the contractile water jet thruster.

The continuous inflation-deflation process imparts the pressure chamber volume differentiation, which is depending on the actuation frequency. A typical relation between the pressure chamber volume and the actuating frequency could be determined based on Eq. (1) below (Stemme et al., 1993);

$$V_{pc} = V_x \sin(2\pi f_{act} t) \tag{1}$$

where V_{pc} is the volume of the pressure chamber, V_x is the volume variation amplitude, f_{act} is the actuator frequency and t is time. Due to the above relation, the sine function gives the positive and negative V_{pc}. If $t = \pi$ or 2π, then $V_{pc} = V_x = 0$. This mean at total deflation, V_x is not equal to zero. Thus, shifted square function had been used to model the contractile pressure chamber volume as shown in Eq. (2) below;

$$V_{pc} = V_x square(2\pi f_{act} t - \pi) + V_x \tag{2}$$

A simulated graph was generated using Matlab software to observe the V_{pc} variation in time (Figure 3). Using square function has an advantage in controlling the frequency using microcontroller. In the designed system, the total inflation would be the maximum V_{pc} and total deflation would make the V_{pc} is equal to zero. It is understand that V_x has nothing to do with the f_{act} but the flow rate of the digested fluid could be influenced by the fact and nozzle area function. Eq. (3) demonstrates the function of V_{pc} and the fluid flow.

$$Q(x,t) = \frac{V_{pc}}{dt} = A_i \frac{dv}{dt} \tag{3}$$

Where Q is the fluid flow rate, A_i is the inlet cross sectional area and dv/dt is the velocity of the fluid. Substituting Eq.(2) into Eq.(3) then we get:

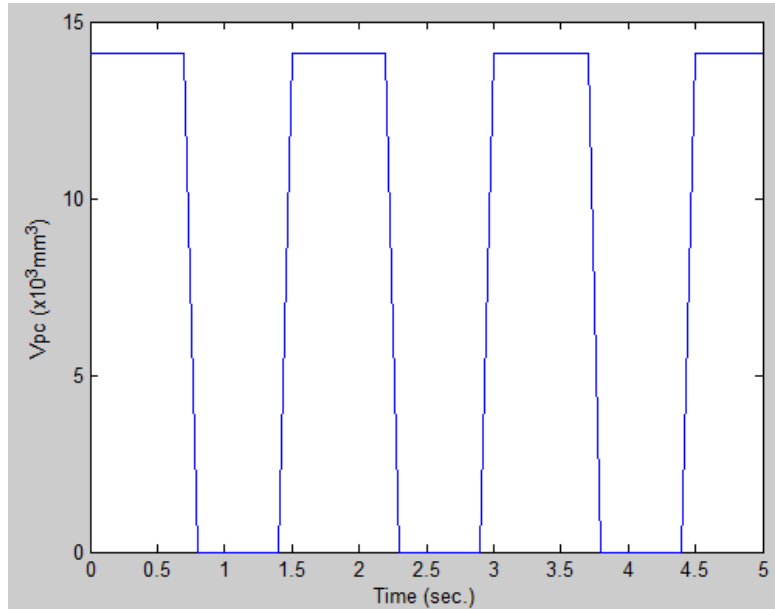$$\frac{dv}{dt} = \frac{V_x}{A_i}\left[square(2\pi ft - \pi) + 1\right] \tag{4}$$

Figure 3. Simulation result to show the V_{pc} changes in time

METHODOLOGY

CWT Fabrication

The 2D CWT was developed based on stacked acrylic layers. As mentioned in Chapter 2, the term 2D refers to length-to-thickness ratio which was 11.67. Translucent acrylic panel with 3mm thickness was cut into two 70mm x 70mm (L x W) panels. These panels acted as cover panels. 6mm thick acrylic panels with several shapes were placed between the cover panels to form a nozzle, inlet and pressure chamber (Figure 4). In this research, the volume for CWT inlet and nozzle were designed based on the real squid mantle-funnel ratio where the internal mantle volume refers to pressure chamber and funnel refers to the nozzle. In order to gain the volume ratio, five squid samples (Loligo spp) with different dorsal mantle length (DML) was taken and their internal volume of the mantle and funnel were measured. The volume ratio result was plotted in a graph as shown in Figure 5. Based on this ratio, the volume of the CWT pressure chamber and nozzle was decided. In this research the nozzle volume was $0.6 cm^3$. Another two acrylic panels with 40mm width were slotted into the pressure chamber. Two pneumatic cylinders (model SMC CJ2B10-75) were attached to these panels. The position of these pneumatic cylinders was adjusted to ensure that the maximum pressure chamber volume was $15 cm^3$ as decided previously.

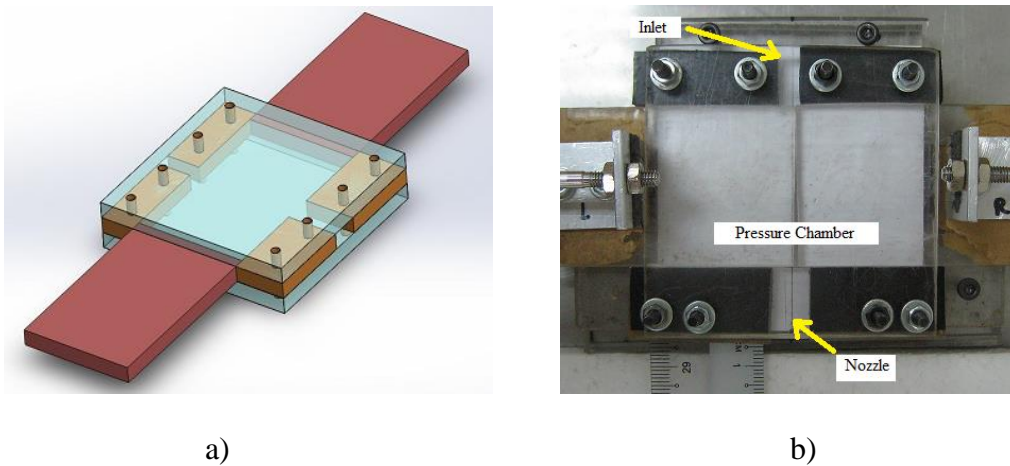a)   b)

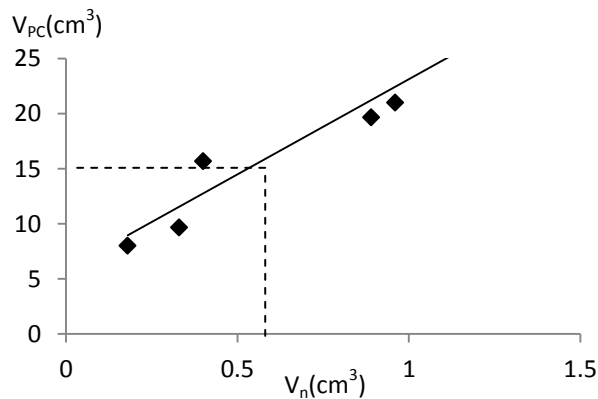Figure 4. Isometric view (a) and top view; (b) of the fabricated 2D CWT.

Figure 5. Pressure chamber-Nozzle volume ratio.

Experimental Setup and Procedure

The 2D CWT was fixed a base to make it rigid and this base was allocated in a 485mm x 365mm x 75mm (L x W x T) water container. The depth of the CWT was set at 10mm under from the surface of the water. Red cooking colour was attached to the inlet and nozzle using drip infusion set. A video camera was set at the top of the CWT to catch video picture of the fluid flow from top view. The image acquisition was set at 35 frames per second (fps). Matlab image processing tool was utilized to measure the volume of the entrained water in the pressure chamber. Those cylinders were supplied with compressed air at different pressure value to provide different actuating force (Figure 6). The calculation for actuating force could be determined by Eq. (5):

$$F_a = A_B P_c \qquad\qquad (5)$$

Where F_a was the actuating force, A_B was the internal bore area of the cylinder and P_c was the supplied pressure which was controlled by the regulator. In this case, A_B was $7.86E^{-5}m^2$. F_a was set to 5N by adjusting the pressure regulator. The oscillating actuator frequency, f_{act} was set to 0.91Hz, 0.77Hz, 0.67Hz, 0.59Hz and 0.53Hz. These frequencies were gained by adjusting the time interval in the microcontroller programme. Arduino UNO was utilized as the microcontroller.
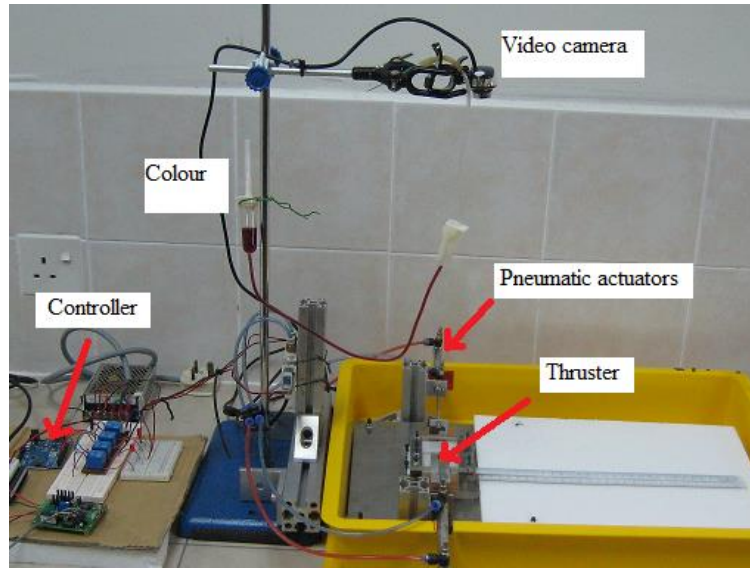

Figure 6. Experimental setup.

RESULTS AND DISCUSSION

This section discusses the gained result from the experimental works. Basically there was no significant fluid flow rate at the initial stage of the inflation process. However, a notable fluid mass motion into the pressure chamber was observed at different actuating frequency at the maximum inflation stage which took around 0.09sec (Figure 7). The higher frequency decreases the ingoing fluid volume and thus reducing the fluid flow rate. Full result is shown in Table 1. The volume measurement was carried out by detecting the red region in Matlab image processing tool and converted as fluid volume.

Figure 7 also depicts the ingoing fluid tended to be attracted at the lateral actuator surface. This phenomenon could be defined using the Navier-Stokes equation previously where the $\partial P/\partial y$ value is greater than the $\partial P/\partial x$. The pressure in x-axis direction became lower because of rapid motion of the actuator in line with the x-axis. Higher frequency enabled less water being entrained into the cavity. This condition occurred as the consequence of the high displacement velocity of the actuator compared to the lower actuating frequency. Higher actuator displacement velocity would not allow much time for the water to fill in the cavity and hence it reduces the number of the entrained water. The relation between the actuating frequency and the fluid flow rate is also shown in Figure 8. Regression analysis was carried out using Minitab software. The result exhibits that the P-value of the relation was 0.014 and the R^2 was 89.9%. The R^2 has answered that there is a strong relation between the frequency and the flow rate. The P-value result shows that the relation of this two parameters falls under normal distribution.
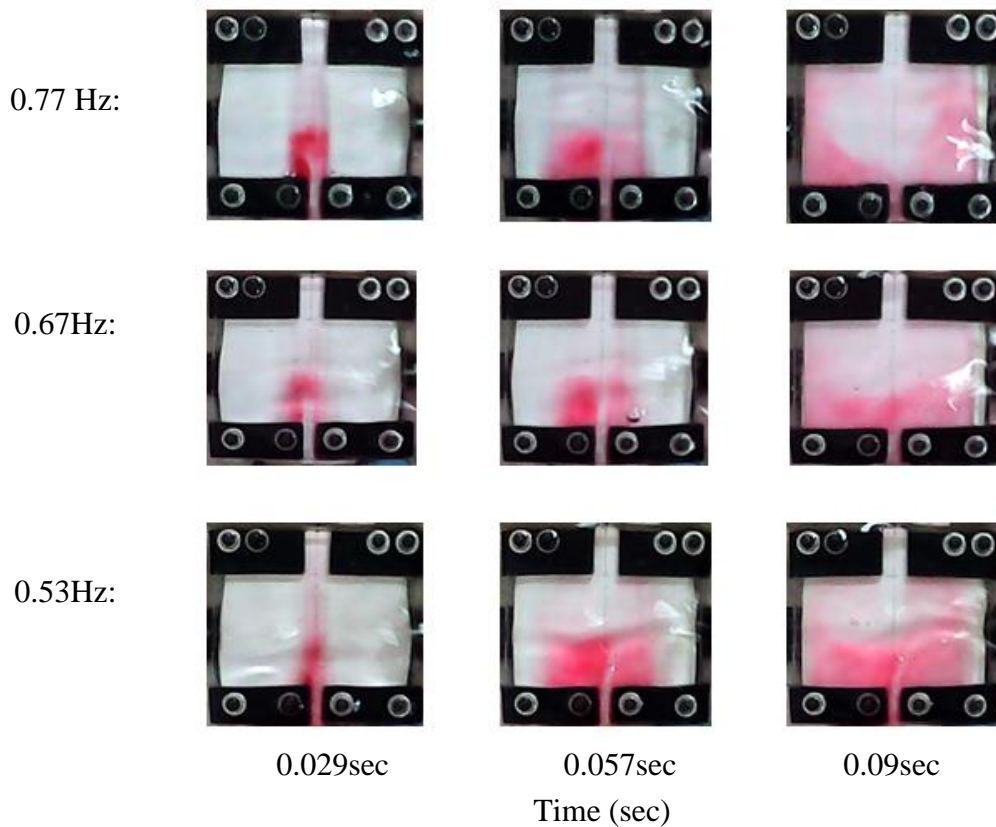
Actuating frequency

Figure 7. Fluid flow trend at different actuating frequency in inflation process.

Table 1. Flowrate result at different actuating frequency.

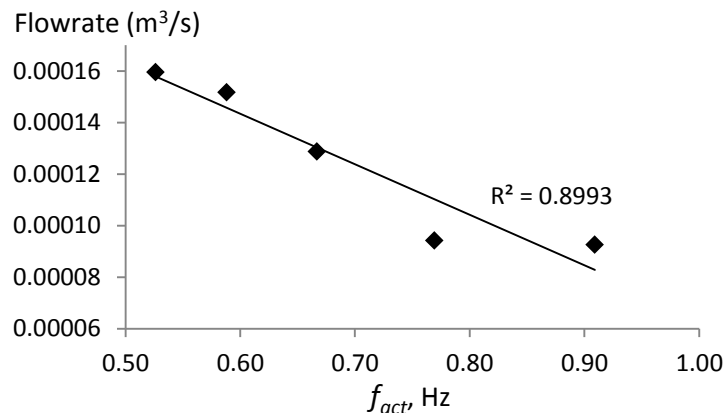| Frequency, f_{act}	Fluid Volume (mm^3)	Flowrate (mm^3/s)
0.91	7938.11	9.26E+04
0.77	8074.08	9.42E+04
0.67	11035.69	1.29E+05
0.59	13008.14	1.52E+05
0.53	13679.57	1.60E+05

Flowrate (m^3/s)

Figure 8. Relation between actuating frequency and fluid flow rate

The Reynolds number was calculated for each of the predetermined actuating frequency. The relation between the Reynolds number and the frequency is presented in Figure 9. Generally the Reynolds number decreases at constant rate as the frequency increase as a result of the decreasing fluid flow rate. The observed Reynolds number was ranged between 22900 and 13300 by regarding to the actuating frequency. The high turbulence of the fluid flow during inflation could be clearly exhibited from Figure 7. The Reynolds number dropped around 9600 at 0.38Hz increment which means turbulence would change at almost 25000 per Hz.
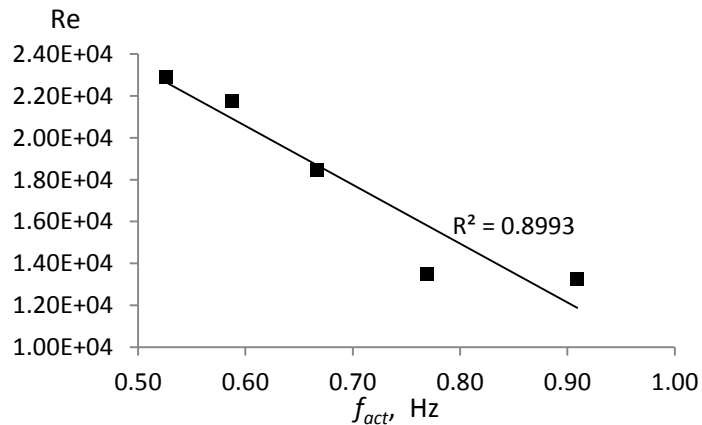
Re

Figure 9. Reynolds number over actuating frequency

CONCLUSION

In general, the actuating frequency has strong influence to the fluid characterization in the pressure chamber of the CWT during inflation process. Higher frequency would decrease the fluid flow rate as well as the Reynolds number. At 0.91Hz frequency, the Reynolds number would reach 22900. This behaviour occurred because of the higher actuator velocity could not provide ample time for the water to fill in the cavity of the pressure chamber and thus decreasing the entrained water volume. In designing the CWT, an optimum actuating frequency must be obtained to achieve maximum mass flow rate during deflation period.

ACKNOWLEDGEMENTS

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