

LDV measurement of boundary layer on rotating blade surface in wind tunnel

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Abstract. Wind turbines generate electricity due to extracting energy from the wind. The rotor aerodynamics strongly depends on the flow around blade. The surface flow on the rotating blade affects the sectional performance. The wind turbine surface flow has span-wise component due to span-wise change of airfoil section, chord length, twisted angle of blade and centrifugal force on the flow. These span-wise flow changes the boundary layer on the rotating blade and the sectional performance. Hence, the thorough understanding of blade surface flow is important to improve the rotor performance. For the purpose of clarification of the flow behaviour around the rotor blade, the velocity in the boundary layer on rotating blade surface of an experimental HAWT was measured in a wind tunnel. The velocity measurement on the blade surface was carried out by a laser Doppler velocimeter (LDV). As the results of the measurement, characteristics of surface flow are clarified. In optimum tip speed operation, the surface flow on leading edge and $r/R=0.3$ have large span-wise velocity which reaches 20% of sectional inflow velocity. The surface flow inboard have three dimensional flow patterns. On the other hand, the flow outboard is almost two dimensional in cross sectional plane.

1. Introduction

The wind turbine rotor aerodynamics strongly depends on the flow around blade. The surface flow on the rotating blade affects the sectional performance. The wind turbine surface flow have span-wise component due to span-wise change of airfoil section, chord length, twisted angle of blade and centrifugal force on the flow. These span-wise flow changes the boundary layer on the rotating blade and affect the sectional performance. Hence, the deep understanding of blade surface flow is important to improve the rotor efficiency. Many researches are done to investigate the wind turbine rotor aerodynamics [1], [2]. However the flow velocity measurements on the blade surface are challenging and there is lack of credible references.

In this study, the detailed surface flow on the rotating blade is investigated experimentally in a model wind turbine. The surface flow velocities are measured by Laser Doppler Velocimetry method.

2. Nomenclature

- c : Local chord [m]
- D : Rotor diameter [m]
- h : Distance from blade surface [mm]
- l : Distance from stagnation point [mm]



- r : Radial position [m]
- R : Rotor radius (=1.2) [m]
- Re_1 : Reynolds's Number
- U_0 : Main flow velocity (=7.0) [m/s]
- U_{3D} : Three dimensional resultant velocity [m/s]
- U_{ref} : Geometrical inflow velocity [m/s]
- V_{rev} : Tangential velocity [m/s]
- w_0 : Spanwise velocity [m/s]
- x : Chord-wise position [m]
- X : Axial position [m]
- Y : Vertical position [m]
- Z : Lateral position [m]
- δ : Boundary layer thickness [mm]
- λ : Tip speed ratio ($=R\omega/U_0$)
- ν : Kinetic viscosity [m^2/s]
- ρ : Air density [kg/m^3]
- ω : Angular velocity [rad/s]
- φ : azimuth angle [degree]
- σ_a : Standard deviation of axial velocity [m/s]
- σ_t : Standard deviation of tangential velocity [m/s]
- σ_r : Standard deviation of tangential and radial velocity [m/s]
- θ_1 : Yaw angle of LDV probe [degree]
- θ_2 : Tilt angle of LDV probe [degree]

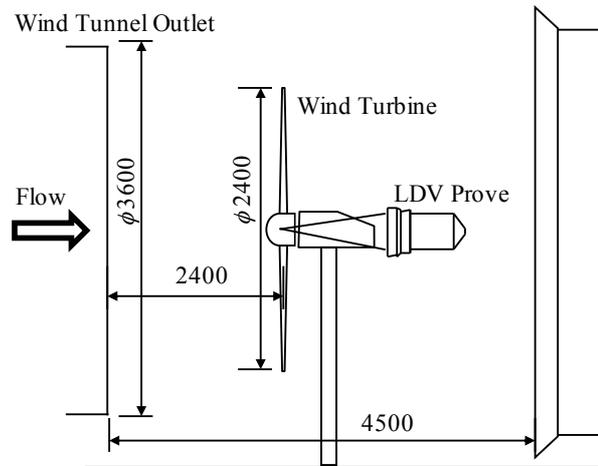


Figure 1 Experimental apparatus

3. Experimental apparatus and method

3.1. Experimental apparatus

The experiments were performed in a Gottingen type wind tunnel with opened test section. Figure 1 shows the schematic drawing of the test section of the wind tunnel. The diameter of the wind tunnel is 3.6m. Maximum wind speed is 30m/s. A three-bladed HAWT model with a diameter 2.4m was set in the test section. Wind turbine blade is twisted and tapered and composed of 4 sections with four kinds of airfoils, with a smooth transition between different airfoil sections. The details of blade configuration are shown on table 1. The blade twist center is set at 0.25 of the local chord. The rotor is set at 1D downstream from wind tunnel outlet. The maximum power coefficient reaches 0.45 at a tip speed ratio of 5.2[3]. Azimuth angle φ is used to detect rotational angle of blade. At origin of φ , target blade is set vertical upward. Flow velocity measurements on the blade surface are performed by a Dantec LDA system.

Table 1 Details of test blade

r/R [-]	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
c [m]	0.0850	0.0928	0.1006	0.1084	0.1162	0.1240	0.1318	0.1396	0.1474	0.0700
Twist angle [degree]	0.00	0.91	1.44	2.86	4.68	5.00	8.33	12.00	18.33	-
Airfoil	NACA6 3-215	NACA6 3-215	NACA6 3-618	NACA6 3-618	NACA6 3-618	DU93-W-210	DU93-W-210	DU91-W2-250	DU91-W2-250	circular

3.2. Experimental Method

To measure velocity field, a LDV system is used, because our laboratory had many experience on LDV. In this experiment, the three dimensional velocity on the rotating blade was determined by measuring three different velocity components through the use of 1D LDV system. The focal length of probe is 1.6m. The measurement volume is a prolonged spheroid shape with diameter of 0.16mm and length 4.67mm. The measuring point is set on the horizontal plane at height of the rotor axis. The target blade passes measurement plane at azimuth angle of 90 degree.

Figure 2 shows the reference LDV probe setting in case of measuring point at $X=0, Z=r$ with probe axis parallel to Z axis. Here the angle between probe axis and rotor plane seeing from above is θ_1 , defined as positive in CW direction. The angle between probe axis and horizontal plane seeing from upstream the wind turbine is θ_2 , defined as positive in rotational direction of wind turbine rotor. Probe setting for measuring the axial component u_1 is $\theta_1=5.0$ [degree], $\theta_2=0$ [degree]. The two beams were set horizontally. To measure velocity on the blade surface, the beam should avoid interference by blade itself: To achieve this, the probe was set with a 5 degree incline to the rotor plane. In this setting, LDV detects the velocity component with 5 degree incline to axial velocity. For measuring the tangential component u_2 , the probe setting was the same as in axial components except the beam azimuth. Two beams were set vertical. For measuring span wise component u_3 , probe setting were $\theta_1=5.0$ [degree], $\theta_2=30.1$ [degree]. The beams were set vertical. Three-dimensional velocity are determined through the use of above three velocity components. The followings equations (1-3) show the velocity conversion procedure.

$$u = u_1 \cos\theta_1 + \left(-\frac{u_2}{\tan\theta_2} + \frac{u_3}{\sin\theta_2} \right) \sin\theta_1 \quad (1)$$

$$v = u_2 \quad (2)$$

$$w = -u_1 \sin\theta_1 + \left(-\frac{u_2}{\tan\theta_2} + \frac{u_3}{\sin\theta_2} \right) \cos\theta_1 \quad (3)$$

u, v and w show velocity in axial, tangential and radial components, respectively.

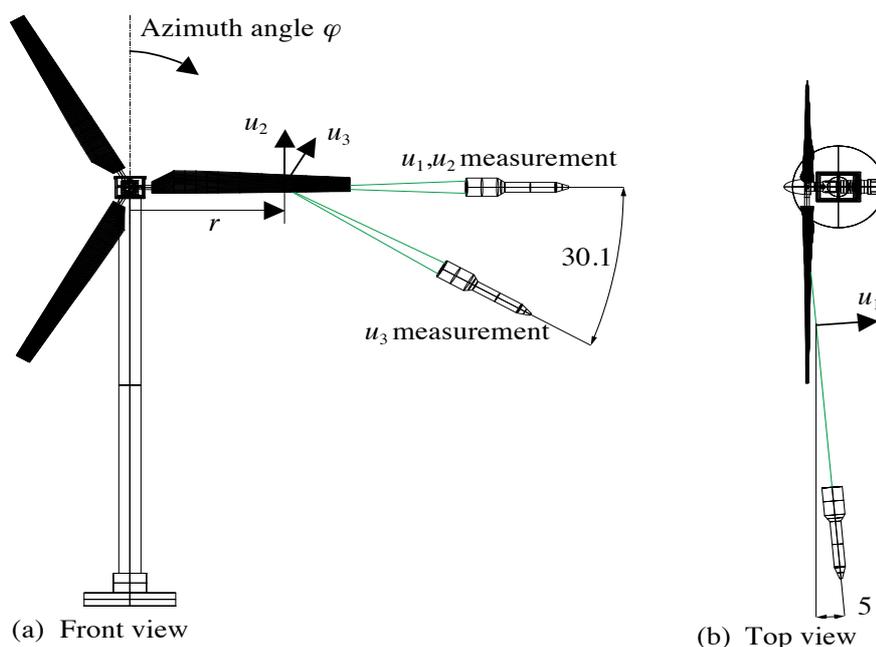


Figure 2 Placement of LDV probe

The number of sample was 10^6 for 1 measuring point. The azimuth angle for each sample was detected by a single reset pulse 1pulse/rev. For averaging the velocity data, 0.1degree azimuth BIN was used.

4. Results and discussion

4.1. Flow around rotor blade

In this section, flow around rotor blade is discussed for $r/R=0.7$ and 0.3. Scalar relative velocity and span-wise velocity components are used.

4.1.1. Velocity field at $r/R=0.7$

Figure 3 shows the velocity field around rotor blade for $r/R=0.7$ at optimum rotor operation. Figures show the velocity contour on suction side. Fig. 3(a) shows the three-dimensional relative velocity. The colour shows the normalized velocity by geometrical relative velocity. The three-dimensional relative velocity is calculated as Eq. (4).

$$U_{3D} = \sqrt{u^2 + (v + V_{rev})^2 + w^2} \quad (4)$$

Here u , v and w are absolute velocity of axial, tangential and radial components in static coordinate which are converted from measuring velocities u_1 , u_2 and u_3 . V_{rev} is tangential velocity base on the rotational speed and radius. U_{ref} is defined as Eq. (5).

$$U_{ref} = \sqrt{U_0^2 + V_{rev}^2} \quad (5)$$

From Fig. 3(a) the flow on the suction surface ($0 < x/c < 0.4$) shows accelerated area $1.3 < U_{3D}/U_{ref} < 1.8$. At $x/c > 0.2$ the flow is decelerated, however the flow is attached to the blade. Fig. 3(b) shows non-dimensional span-wise velocity, w_0/U_{ref} . Here w_0 means the velocity component perpendicular to airfoil cross section. The value is positive when flow direction is outward. w_0 is calculated from tangential velocity, v and radial velocity, w .

$$w_0 = v \cos \varphi + w \sin \varphi \quad (6)$$

From Fig. 3(b), the surface flow has outward span-wise velocity on leading edge. The surface flow in leading edge part ($x/c < 0.4$) is uniform with outward components, on the other hand the surface flow in trailing edge part ($x/c > 0.6$) is non-uniform. The surface flow in trailing edge part is turbulent. Therefore, the blade surface flow for $r/R=0.7$ is basically two dimensional with small span-wise component in both leading and trailing edge.

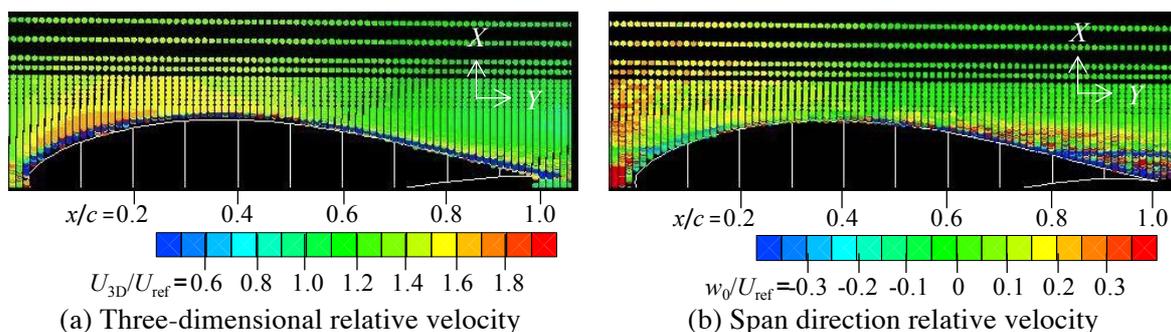


Figure 3 Velocity field ($r/R=0.7$)

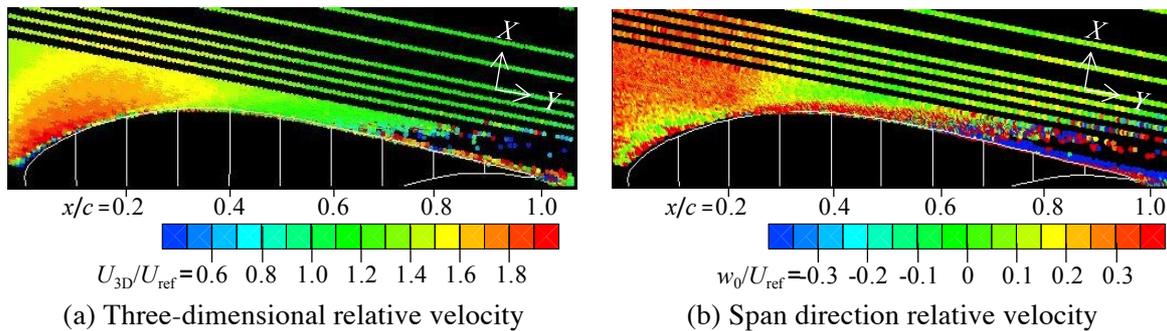


Figure 4 Velocity field ($r/R=0.3$)

4.1.2 Velocity field at $r/R=0.3$

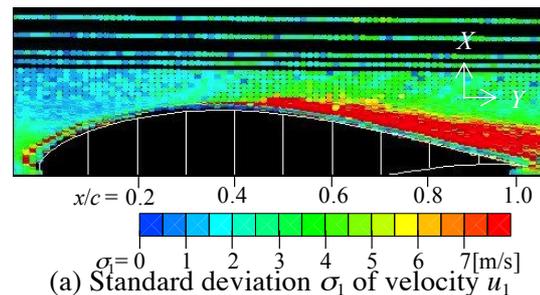
Figure 4 shows the velocity field around rotor blade for $r/R=0.3$ at optimum rotor operation. Figure 4(a) shows non-dimensional relative velocity contour. From Fig. 4(a) the flow velocity on the blade surface is increased ($U_{3D}/U_{ref}=1.8$) at $0 < x/c < 0.3$. Similar speed up is observed on outboard, $r/R=0.7$, the speed up ratio on inboard is stronger than that on outboard. The flow velocity is decreased and pressure is recovered at $x/c > 0.3$. Black area is seen at $x/c > 0.7$: in this area the number of measured particle is not enough. Near trailing edge, the flow on blade surface seems to be separate. So, the number of tracer particle which pass the measurements volume becomes less.

Figure 4(b) shows the span-wise velocity distribution. From Fig. 4(b), the span-wise velocity on blade surface is $w_0/U_{ref} > 0.2$ at $x/c > 0.2$. The surface flow is not on the plane of airfoil, it includes large out of plane component.

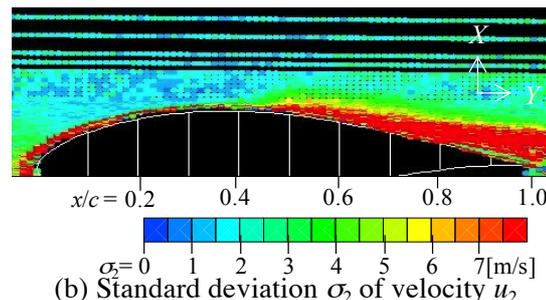
From above discussion, the flow on inboard has span-wise velocity and the resultant velocity becomes larger than that of resultant velocity based on axial and tangential velocity. The negative pressure on blade inboard is stronger than that on two-dimensional measurements.

4.2. Standard deviation of velocity

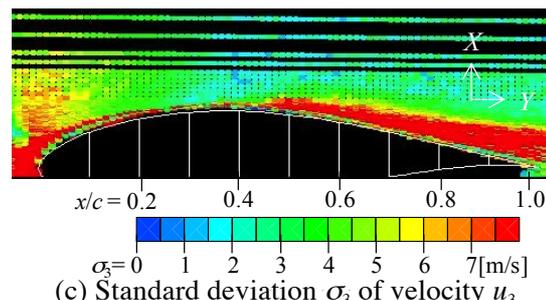
In this section the surface boundary layer is discussed by standard deviation of velocity. Figure 5(a), (b) and (c) show the standard deviation of measured three components, respectively u_1 , u_2 and u_3 . From Fig. 5(a), standard deviation at $0.2 < x/c < 0.4$ is in a range of $0 < \sigma_1 < 2.0$. On the other hand, for $x/c > 0.5$ it is $\sigma_1 \geq 5.0$. The height from blade surface which shows large σ_1 becomes higher as close to trailing edge. From Fig. 5(b) σ_2 for leading edge shows large value of 5.0-8.0m/s. These large σ show increased flow velocity at leading edge. On the trailing edge side $x/c > 0.5$, σ_2 shows the similar tendency as σ_1 . From Fig. 5(c), σ_3 show the similar tendency as σ_1 and σ_2 . The flow on blade surface of $x/c > 0.5$ at $r/R=0.7$ shows strong deviation in every components. It



(a) Standard deviation σ_1 of velocity u_1



(b) Standard deviation σ_2 of velocity u_2



(c) Standard deviation σ_3 of velocity u_3

Figure 5 Standard deviation of velocity ($r/R=0.7$)

is estimated that the boundary layer is turbulent at $x/c > 0.5$. Near the leading edge, σ_3 show larger value than σ_1 and σ_2 . It seems that there is effect of the spatial resolution. This measurement gets volume average value in some radial direction due to the use of long focal 1D LDA. The incline angle between rotor plane and LDA probe axis can prevent laser shutdown by the blade and measure surface velocity. However, it also reduces the spatial resolution in the height direction. The tilted angle to capture span-wise component also reduces the spatial resolution in chord-wise direction. Decrease in the spatial resolution makes it difficult to determine local velocity with a sharp change. So, the measuring of the velocity distribution on boundary layer seems to be less accurate than that of outside.

4.3. The thickness of boundary layer

The three dimensional boundary layer of a rotating blade is a very complex problem. The examination of boundary layer may verify the stagnation point of the airfoil, though it is difficult to detect by these suction surface measurements. The flow passing close to surface is also difficult to detect. Three dimensional distributions of the velocity components make the problem more complex. Due to the lack of information, adequate treatment of these measuring data to discuss the boundary layer is impossible. So, the measured thickness of boundary layer on the blade surface is compared to a simple flat plate boundary layer's formula [4]. On the blade surface the flow has acceleration by blade thickness and cumber. The boundary layer on blade surface is different from flat plate one by pressure distribution. In this discussion, the boundary layer for a flat plate model is obtained by the following equations.

$$\text{Laminar boundary layer : } U = \left\{ 2\left(\frac{y}{\delta}\right) - 2\left(\frac{y}{\delta}\right)^3 + \left(\frac{y}{\delta}\right)^4 \right\} U_e \quad (7)$$

$$\text{Turbulent boundary layer : } U = \left\{ \left(\frac{y}{\delta}\right)^{\frac{1}{7}} \right\} U_e \quad (8)$$

here, y is height from body surface, δ is thickness, U_e is free stream velocity outside of boundary layer. For this discussion the free stream velocity is selected as maximum velocity at fixed chord-wise position. The thickness δ is calculated from model formula.

$$\text{Laminar boundary layer : } \delta = \left(\frac{5.5}{\sqrt{Re_1}} \right) l \quad (9)$$

$$\text{Turbulent boundary layer : } \delta = \left(\frac{0.381}{Re_1^{\frac{1}{5}}} \right) l \quad (10)$$

Here, l is the length from tip along body surface. Re_1 is Reynolds's number based on local length from leading edge, l .

$$Re_1 = \frac{U_e l}{\nu} \quad (11)$$

Here, ν is kinematic viscosity, l is the length from stagnation point along blade surface.

Fig. 6 (a), (b), (c) are the velocity profile on blade surface for $r/R=0.7$ under optimum rotor operation. The horizontal axis of Fig. 6 shows three dimensional resultant velocity, U_{3D} and vertical axis shows the height from blade surface. Blue line show measured profile. Red line shows the laminar

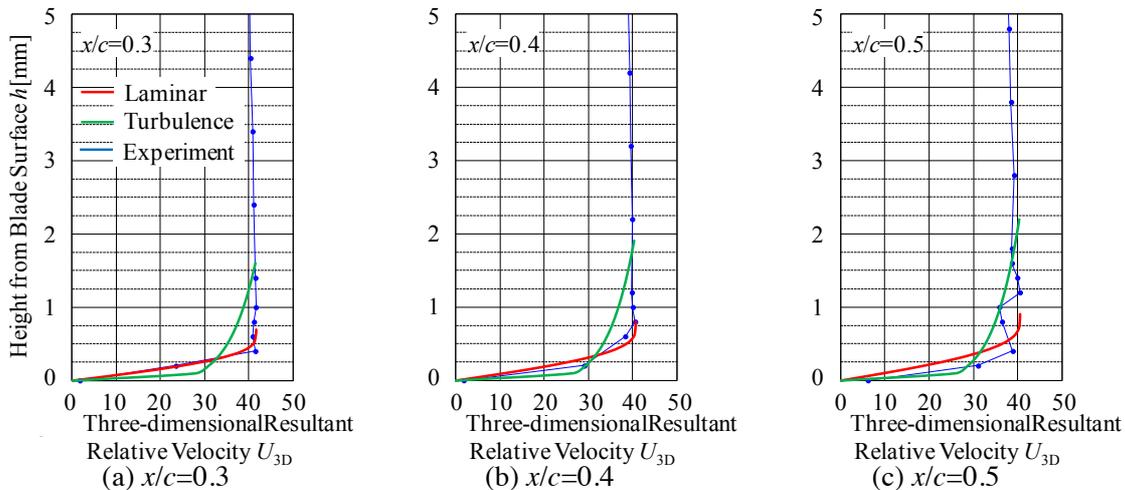


Figure 6 Velocity profile on blade surface ($r/R=0.7$)

profile from Eq. (3). Green line shows the turbulent profile from Eq. (4). The maximum height of each lines means the boundary layer thickness from Eq. (5) and (6). Form Fig. 6(a) the velocity profile at $x/c=0.3$ is close to laminar profile for $h<0.6\text{mm}$. The boundary layer at $x/c=0.3$ is thought as laminar. Form Fig. 6(b) the velocity profile at $x/c=0.4$ is close to turbulent profile in $h<0.2\text{mm}$ and laminar in $0.6<h<0.8$. Form Fig. 6(c) the profile at $x/c=0.5$ is close to turbulent profile for $h<1.4\text{mm}$. The boundary layer at $x/c=0.5$ is thought as turbulent. The blade surface boundary layer seems to move from laminar to turbulent at $0.3<x/c<0.5$. This transition area agrees well to discussion from the velocity deviation in Sec. 4.2.

5. Summary

The detailed flow measurement on rotating blade surface by a Laser Doppler Anemometry is carried out in order to understand rotor surface flow. The following findings are verified:

The surface flow on leading edge for $r/R=0.3$ have large span-wise velocity which reaches up to 20% of inflow velocity. The surface flow inboard have three dimensional flow patterns. On the other hand, the flow outboard is almost two dimensional in cross sectional plane.

From the results of velocity deviation in flow, the boundary layer for $r/R=0.7$ transits from laminar to turbulent at $x/c=0.5$.

By the results of velocity profile in boundary layer, the boundary layer for $r/R=0.7$ transits from laminar to turbulent at $0.3<x/c<0.5$. This transition position agrees well the results obtained by velocity deviation.

The velocity distribution in the boundary layer seems to be less accurate than that of outside the boundary layer.

Therefore, the measurement requires improvements on the spatial resolution of the LDV system for a more thoroughly discussion. Currently, to improve the spatial resolution, it is proposed and being used a three-dimensional LDV arrangement.

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