VIBRATION ANALYSIS OF A V-BELT DRIVE IN VARIABLE CONDITIONS OF PULLEYS MISALIGNMENT

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This paper deals with vibration analysis of a V-Belt drive based on altering conditions of pulleys misalignment. The main question this paper tries to answer is whether there is a direct and measurable relation between the pulley misalignment conditions and vibration of the machine. Using the ADASH vibration analyser with accelerometer sensors and laser speed sensor attached, we gathered data from our test stand purposely build for this task. Designing of the test stand is described as well as some basics of vibration measurement and belt drive operation. Next a testing methodology is described where several conditions of parallel and angular misalignment as well as different belt tension conditions were simulated using adjustability of our testing stand. Then in data analysis part we look at relations between multiple measurements of different pulley misalignment conditions viewed in time domain vibration analysis. [VSB-TUO].

KEYWORDS

VIBRATION ANALYSIS, PULLEY MISALIGNMENT, V-BELT

1 INTRODUCTION

Vibration analysis is a method used to measure vibration levels and frequencies of rotating machinery. Over the years it has become an important tool for evaluation of technical condition of machines and for their residual life prediction. Some level of vibration has always been a part of rotating machinery operation and the first vibration analysis was performed solely using human senses of touch and hearing and was then analysed in brains of skilful workers. In present the vibration analysis gives us precise information about individual machine faults using high sensitivity accelerometers and signal analysers with modern software. To evaluate the vibration signal two most common approaches are used. The time domain analysis, which gives us information about severity of vibration usually expressed in vibration velocity and the frequency spectrum analysis which applies Fast Fourier Transform on the time waveform. In frequency spectrum each component fault in machine is represented by its specific frequency relative to machines running speed expressed in harmonics of running speed (1xRPM, 2xRPM etc.). To successfully evaluate the technical condition of each machine, both approaches must be used. One of the fields of applications of vibration measurement in industry is a V-Belt drive. This type of drive can be a source of severe vibration especially in misaligned conditions. The aim of this paper is to determine how v-belt drive pulleys misalignment effects machine overall vibration. [VSB-TUO], [PLANT SERVICES].

2 TEST STAND DESIGN AND FUNCTION

For testing various conditions of belt drive the vibration test stand was developed. The main task in its development was to build versatile and modular testing device. This test stand can simulate machine faults related to V-belt pulley alignment conditions, imbalance, shaft alignment and universal joint alignment and phasing.

In the first phase of development rigid steel frame with low natural frequency was designed. The frame was appropriately sized in order to accommodate all parts while remaining compact and transportable. Then we carefully picked necessary components starting with an AC motor from local company VYBO Electric which also supported us with required frequency converter and a gearbox. All connecting shafts were machined by skilful students from our university department. A power transmission from the AC motor to the gearbox is provided by a complex drive. The first part of the drive consists of a straight shaft connect to the AC motor with use of a flexible coupling. On the end of the shaft there is a drive pulley as the first part of the belt drive system. The straight shaft is then supported by a first pair of pillow block bearings which provide sufficient rigidity to prevent shaft bending due to a force acting on the shaft caused by a belt pretension. [VSE O PRUMYSLU].

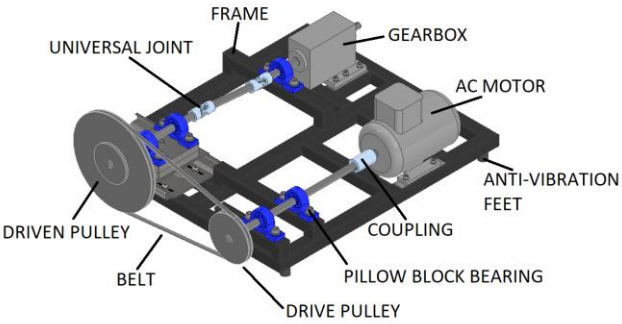


Figure 1. 3D model of a newly designed test stand

2.1 Belt Drive

When designing the belt drive, we used a standard SPZ Series V-belt which is according to ISO 155:2019 standard applicable for use with supported AC motor with maximum power of 0,75 kW. The main force acting in a belt drive is a circumferential force F, which is the force that is responsible for torque transmission from drive pulley T1 to driven pulley T2 as well as power based on rotational speed of both pulleys.

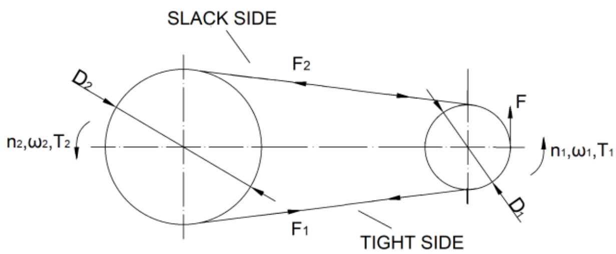


Figure 2. V-belt drive

To create the most representative example of a common belt drive we first calculated appropriate centre distance E which is supposed to be between minimum and maximum values based on pulleys pitch diameters. The centre distance has also been adjusted based on other required dimensions of the device.

Minimum and maximum values for centre distance of pulleys.

$$E_{MIN} = \frac{1}{\sqrt{2}} \cdot (D_2 - D_1) \tag{1}$$

$$E_{MAX} = 2 \cdot (D_1 + D_2) \tag{2}$$

Picked preliminary centre distance of pulleys.

$$E = 415 \text{ mm} \tag{3}$$

Belt drive composes of two arc-shaped sections represented by their wrap angles around pulleys and two straight belt sections. First, we calculated a wrap angle α of a belt around drive pulley.

$$\alpha = 2 \cdot \arccos\left(\frac{D_2 - D_1}{2 \cdot E}\right) \tag{4}$$

Then an included angle which is identical for both pulleys.

$$\gamma = 90 - \frac{\alpha}{2} \tag{5}$$

Wrap angle δ of a belt around driven pulley.

$$\delta = 180 + 2 \cdot \gamma \tag{6}$$

Knowing these belt angles a preliminary belt length L was calculated and then corrected to fit a standard belt size SPZ V-belt with length L_i.

$$L = 2 \cdot E \cdot \sin\frac{\alpha}{2} + \pi \cdot D_1 \cdot \frac{\alpha}{360} + \pi \cdot D_2 \cdot \frac{\delta}{360} \tag{7}$$

$$L_i = 1520\ mm \tag{8}$$

Based on the equation (7) an actual centre distance was calculated.

$$E_i = 455{,}2\ mm \tag{9}$$

2.2 Pulleys Alignment and Belt Tensioning

Even though this designed belt drive will not be under the full stress due to low power transmission only effected by friction of gears, bearings, U-joints and a friction between pulleys and V-belt profile, we wanted to create a standard for proceeding measurements. This standard will then represent an initial position for all future adjustments and simulations of all types of misalignment options. The initial position represents a position where both pulleys are perfectly parallelly and angularly aligned and V-belt is properly tensioned.

There are several types of pulley misalignment and their combinations displayed in chart below. [theNEWS].

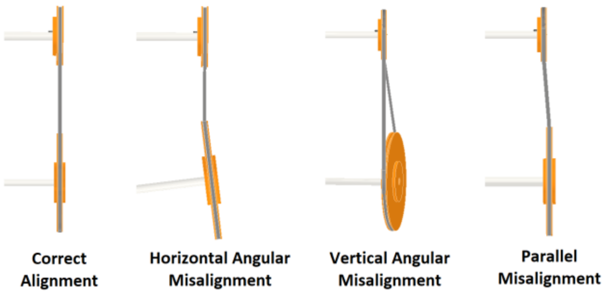


Figure 3. Types of Pulley Misalignment

Number of methods is used to correct pulley misalignment although rarely any of these methods provide information about actual relative position of pulleys quantified by angle or distance between their planes. On our testing device we were only able to simulate parallel and horizontal angular misalignment conditions. [VSE O PRUMYSLU].

To achieve the base position in which both pulleys are perfectly aligned, we first used the Easy-Laser Shaft Alignment tool to align drive belt shaft with coupling and electric motor shaft. Then we used PULLALIGN tool to align both pulleys to correct all forms of misalignment. Before every measurement, therefore simulation of any type of misalignment, we corrected pulleys to their base position using PULLALIGN tool.

Figure 4. Use of PULLALIGN tool to correct basic angular misalignment

One of the most important parameters when testing the belt drive vibration is the belt tension. The belt tension was measured before every test using belt tension tester tool TYMA BELT CONTROL 1.

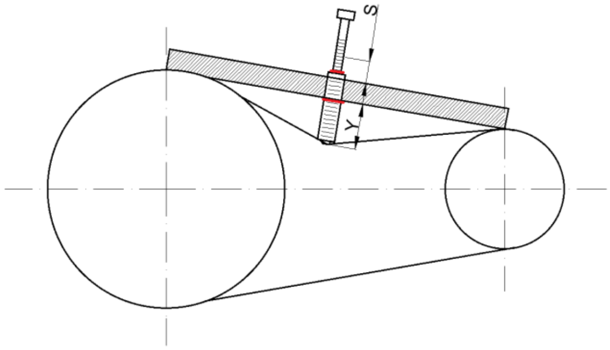


Figure 5. Diagram of belt tension measurement using the belt tensioner tool

Whenever we were tensioning the belt, we first calculated proper deformation of belt span Y using equation.

$$Y = \frac{15}{1000} \cdot L_M \tag{10}$$

Free belt span length can be either measured directly using precise measuring tape or it can be calculated based on previously mentioned wrap angle α. Belt pretension force F_O is then based on included angle δ and measured deformation S from belt tensioner tool.

$$L_M = A \cdot \sin\frac{\alpha}{2} \tag{11}$$

$$F_O = \frac{S/_2}{\sin \delta} \tag{12}$$

2.3 Parallel Misalignment

To measure the parallel misalignment severity, we used a straight edge attached to one of the pulleys. While moving one or both pulleys in their axial direction we measured the relative distance X between pulleys by measuring the gap between the pulley and the straight edge.

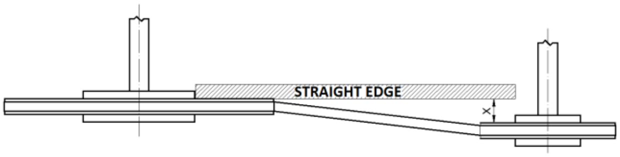


Figure 6. Parallel misalignment measurement

2.4 Horizontal Angular Misalignment

In order to simulate conditions of horizontal angular misalignment the newly developed test stand gives us ability to rotate the driven pulley. Shaft of the driven pulley is supported by a pair of pillow block bearings which are then attached to a rotational base. The rotational base consists of two aluminium plates joint with a bolt. By loosening the bolt, we can rotate the upper base plate against the lower plate which is then attached to a belt tensioner. [PLANT SERVICES], [IOPSCIENCE].

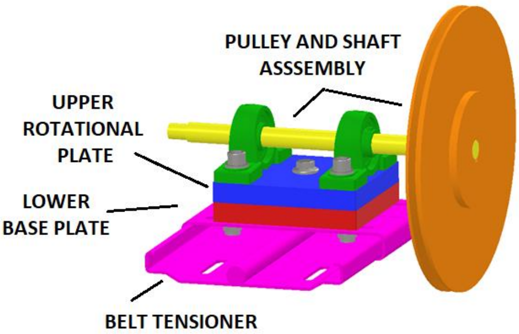


Figure 7. Detail of angle adjustment assembly from test stend

Once a desired pulley angle was achieved, the upper rotational plate can be fixed in position by inserting a locking pin in one of predrilled holes. Standard adjustment of our test stand gives user 8 positions in which the rotational plate can be fixed ranging from +4° to -3°.

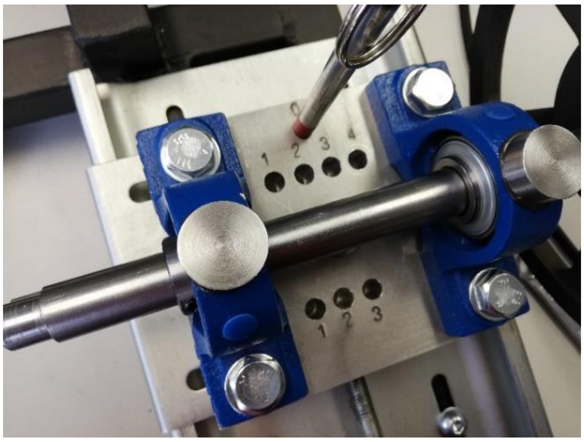
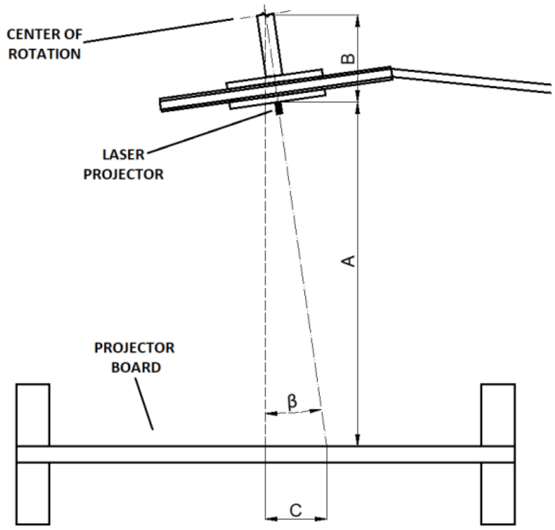


Figure 8. Detail of predrilled holes for angle adjustment

To confirm the angle adjustment, we developed a special single purpose laser shaft angle measurement tool. It consists of a laser projector which is inserted into a shaft carrying the driven pulley and a projector board with angle scale. Knowing the distance between the laser projector and the projector board B and a distance between each line on angle scale C we can accurately calculated the angle β of the rotational upper plate, therefore a severity of horizontal angular misalignment of the belt drive.



The relative angle between ideal angular alignment of both pulleys and misaligned position of the driven pulley is represented by angle β, to calculate the angle β we used a simple trigonometric equation:

$$\beta = arctan\left(\frac{C}{A+B}\right) \tag{13}$$

3 VIBRATION MEASUREMENT

The focus of this research paper was to figure out if there is a direct and measurable relation between different conditions of pulleys misalignment and vibration of the machine. In order to confirm assumption of machine vibration increasing proportionally based on severity of pulleys misalignment we performed series of tests in which we were increasing level of pulleys misalignment mainly by changing relative position of driven pulley to solid position of drive pulley. In other series of tests, we were changing the belt tension as well.

The vibration data collection was performed using Adash A4400 VA4 Pro vibration analyser. For every measurement we compared data in time domain as well as in frequency domain using waterfall diagrams. **All measurements were submitted to ISO 20816-1 Mechanical vibration standard.** [VSB-TUO].

The vibration was measured using 3-axis accelerometer attached with neodymium magnet to measurement points on each pillow block bearing supporting pulleys shafts. All displayed data come from vibration measurement from the sensor attached to measurement point closest to the driven pulley.

Before performing any belt vibration measurement simulations, we first measured vibration with belt disconnected. This test gave us information about frequencies occurring in system due to the electric motor vibration represented with frequency spectrum of this measurement. [IOPSCIENCE], [14th IMEKO TC10 WORKSHOP TECHNICAL DIAGNOSTICS], [ENGINEERING SPECIFIER].

This test as well as all upcoming tests were performed with 25 Hz operating frequency of the electric motor.

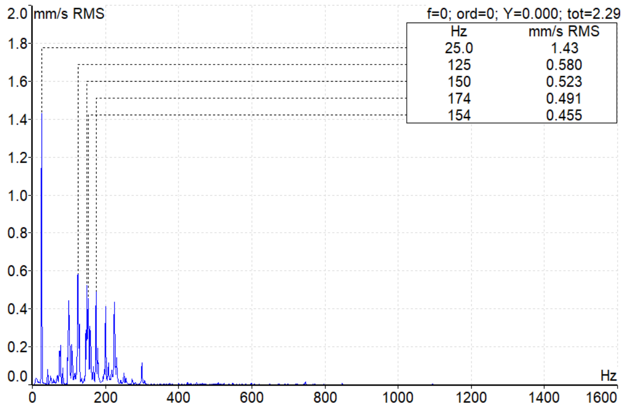
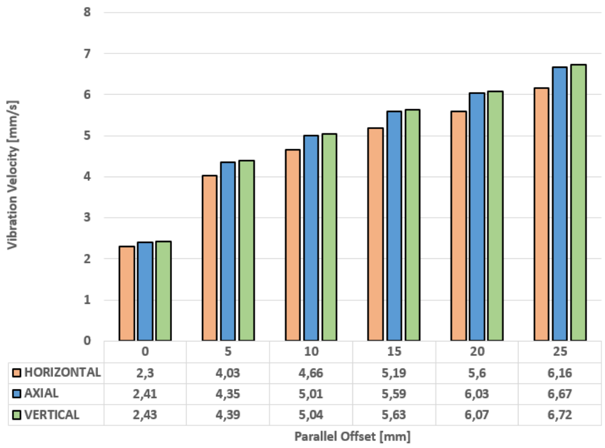


Figure 9. Frequency spectrum (vibration of electric motor excited on pillow block bearing)

In this spectral data the most dominant frequency is 1x rotational speed caused by imbalance of the rotational assembly. Other frequencies (5x and 6x) are much less dominant in spectrum and most likely represent insufficient rigidity of bearing and motor mounts i.e., the mechanical looseness of rotational assembly. [PLANT SERVICES].

3.1 Parallel misalignment – vibration measurement results

As mentioned before the severity of parallel misalignment was represented by offset distance X between both pulleys. When performing the test, we first measured vibration velocity with accelerometer attached to measuring point closest to the driven pulley when both pulleys were perfectly aligned. Then we increased offset distance X by moving driven pulley in axial direction and repeated the vibration measurement. [PLANT SERVICES], [IOPSCIENCE].

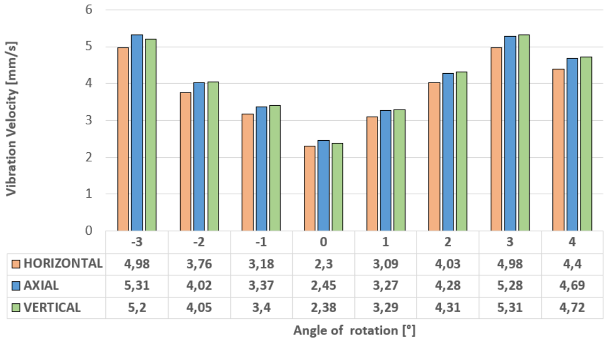


	0	5	10	15	20	25
HORIZONTAL	2,3	4,03	4,66	5,19	5,6	6,16
AXIAL	2,41	4,35	5,01	5,59	6,03	6,67
VERTICAL	2,43	4,39	5,04	5,63	6,07	6,72

Figure 10. Measurement results representing relation between vibration velocity and parallel misalignment

3.2 Horizontal angular misalignment – vibration measurement results

In this case the severity of horizontal angular misalignment is represented by the angle of rotation β which is the relative angle between ideal angular alignment of both pulleys and their misaligned position. First measurement was performed with both pulleys perfectly aligned and belt tensioned according to specifications. The we were increasing the angle β by rotating driven pulley in clockwise direction (from +4° to -3°). Increasing the angle further away in both directions caused the belt falling of pulley. Before each measurement it was also very important to readjust the belt tension because any change in horizontal angular misalignment also changes relative axial distance of pulleys. [PLANT SERVICES].



	-3	-2	-1	0	1	2	3	4
HORIZONTAL	4,98	3,76	3,18	2,3	3,09	4,03	4,98	4,4
AXIAL	5,31	4,02	3,37	2,45	3,27	4,28	5,28	4,69
VERTICAL	5,2	4,05	3,4	2,38	3,29	4,31	5,31	4,72

Figure 11. *Measurement results representing relation between vibration velocity and angular misalignment*

4 CONCLUSIONS

With the first measurement, we verified the condition of the assembly, when we disconnected the belt and thus determined the influence of vibrations from the electric engine. According to the measurement values (Fig. 9), it can be concluded that the rotary assembly is out of balance. Furthermore, it is possible to determine the probable occurrence of insufficient rigidity of bearing and engine. Nevertheless, these values are sufficient for laboratory measurements.

The measurement of the parallel misalignment (distance X) showed us a fairly, predictable state of development of the assembly's behavior. We will start from the values shown in Fig. 10. For comparison, it was measured with the belt on and zero deviation. This was followed by gradual adjustment of the deviation (X) from the ideal state up to 25 mm (0, 5, 10, 15, 20, 25) mm. It can be observed that as the deviation increases, the vibration speed deteriorates. When the deviation was set to 5 mm, there was a more drastic deterioration in the vibration speed, but from 5 mm to 25 mm, the vibration speed deteriorates by small values. A deviation of more than 25 mm caused the belt to rotate. Of course, misalignment is undesirable for practical use and may lead to incorrect functioning of technical equipment.

When measuring the horizontal angular misalignment (rotation angle β) we start from Fig. 11. To determine the value for comparison, the pulleys with the attached belt were brought to the state β = 0°. From values -3° to +3°, an almost identical increase in the deterioration of the vibration speed can be observed on both sides, thus the curve forms a parabola. At +4°, we can see a slight decrease in the vibration speed, but this value was already critical for such a small device and cannot be taken seriously, because the belt partially rotated, but the value was still measured. For the -4° condition, which is not even listed here, no values could be measured because the belt slipped out of the pulleys immediately after the device started up. Again, it must be noted that horizontal angular misalignment conditions are undesirable for most technical equipment and lead to a reduction in the condition of individual machine units.

It is also necessary to think about the effect of belt tensioning because incorrect tensioning can lead to distortion of measurement values, as well as damage to the belt, etc...

Overall, it can be stated that use of this measurement method gives us sufficient results to describe the behavior of a V-belt drive in variable conditions of pulleys misalignment. Also compared to other methods, for example measuring boundary V-belt vibrations using displacement sensor and microphone, it is less time consuming, and, in some cases, it can be applied to vibration measurement in situ. [JOURNAL OF SOUND AND VIBRATION].

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REFERENCES

[VSB-TUO] Blata J., Juraszek J. Metody technicke diagnostiky teorie a praxe [Methods of Technical Diagnosis of Theory and Practise]. 1st ed. Ostrava: VSB-TUO, 2013. ISBN 978-80-248-2997-5.

[PLANT SERVICES] Bacidore M. How Vibration Analysis Can Detect Alignment Problems, [online]. 2014. Available from https://www.plantservices.com/articles/2014/vibration-analysis-detect-alignment-problems/

[IOPSCIENCE] Kiselev M. I., Pronyakin V. I., Tulekbaeva A. K. Technical Diagnostics Functioning Machines and Mechanisms, IOP Publishing Ltd, [online]. 2018. Available from https://iopscience.iop.org/article/10.1088/1757-899X/312/1/012012/meta

[ENGINEERING SPECIFIER] Houghton International, [online]. 2018. Available from https://www.engineeringspecifier.com/machining/how-misalignment-in-rotating-machinery-can-affect-you

[IOPSCIENCE] Krawiec P., Pajtasova M., Meler F., Wargula L. Testing Functional Features of V-bel Transmissions, IOP Publishing Ltd, [online]. 2020. Available from https://iopscience.iop.org/article/10.1088/1757-899X/776/1/012008

[14th IMEKO TC10 WORKSHOP TECHNICAL DIAGNOSTICS] Sapozhnikova K., Promin A., Druzhinin I., Taymanov R., Metrological Self-check as a Perspective Trend of Technical Diagnostics, D. I. Mendeleyev Institute of Metrology, [online]. 2013. Available from https://www.imeko.org/publications/tc10-2016/IMEKO-TC10-2016-037.pdf

[theNEWS] Sullivan D. R., Explaining V-belt Drive Misalignment, HVAC CONSTRACTING, [online]. 2010. Available from https://www.achrnews.com/articles/113731-explaining-v-belt-drive-misalignment

[VSE O PRUMYSLU] Blata J., Projevy nesouososti strojnich zarizeni [Manifestations of Misalignment of Machinery], Rizeni a udrzba prumysloveho podniku, [online]. 2016. Available from https://www.vseoprumyslu.cz/udrzba-a-diagnostika/termodiagnostika/projevy-nesouososti-strojnich-zarizeni.html

[JOURNAL OF SOUND AND VIBRATION] J. MOON, J.A. WICKERT,RADIAL BOUNDARY VIBRATION OF MISALIGNED V-BELT DRIVES, Journal of Sound and Vibration,Volume 225, Issue 3,1999, Pages 527-541, ISSN 0022-460X, https://doi.org/10.1006/jsvi.1999.2258.

Available from: https://www.sciencedirect.com/science/article/pii/S0022460X99922587)

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