Polar and Orbit Plot Analysis for Unbalance Identification in A Rotating System

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Abstract: *This paper presents a detailed analysis of polar and orbit plots considering a non-faulty shaft and one with an unbalanced mass attached to it. Polar Plot analysis was done in order to determine the amplitude of vibration and the phase difference between faulty and non-faulty case. Also the orbit plot analysis provides a clear image of the two different cases, in which the area under the ellipse can be considered as the measure of the unbalance.*

I.   Introduction

Unbalance is defined as an unequal distribution of mass causing the mass axis to differ from the bearing axis. During rotation, the unequal mass along with the radial acceleration due to rotation create a centrifugal force. This results in force on the bearings and/or vibration of the bearings. Balancing is a procedure in which the mass distribution of a rotor is assessed and if necessary, adjusted via addition or subtraction of weight to ensure that the vibration of the journals and/or forces on the bearings are within specified limits. Vibration is a mechanical movement where an object oscillates about an equilibrium point. It commonly produces unwanted sound and wastes energy. Vibration in rotating equipment can greatly reduce the life of the equipment and the bearings. Before studying the basic principles of balancing, one must keep in mind that there are many causes of vibration other than unbalance. In some cases, balancing may result in only a partial or temporary reduction in vibration, while in other cases balancing is the only effective course of action.

Mechanical unbalance, which produces a force at 1 X RPM, has been found to be one of the most common causes of machinery vibration, present to some degree on nearly all rotating machines. Polar Plot and Orbit Plot analysis are methods to determine the unbalance in the machine. By the nature of the plots, one can easily determine the type of fault in the machine and can take remedial action immediately in order to prevent any catastrophic effects on the machine.

II.   Materials And Methodology

2.1Experimental setup and procedure of data collection:

Considering the main cause of rotating machine vibration as unbalance, a test rig for experimental validation of the model based identification technique was built. Schematic representation of the experimental set has been shown in the figures below.
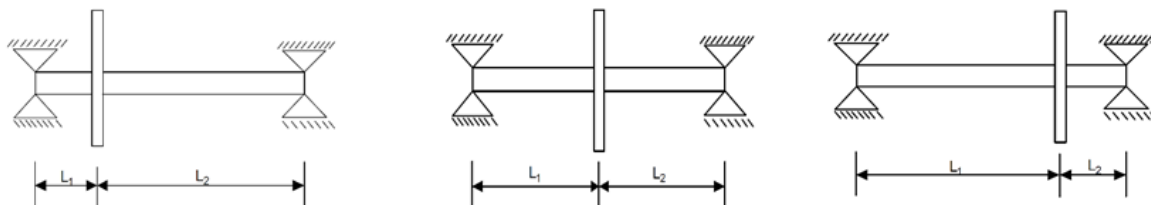

Figure 5: Schematic representation of the experimental set up (no fault case)
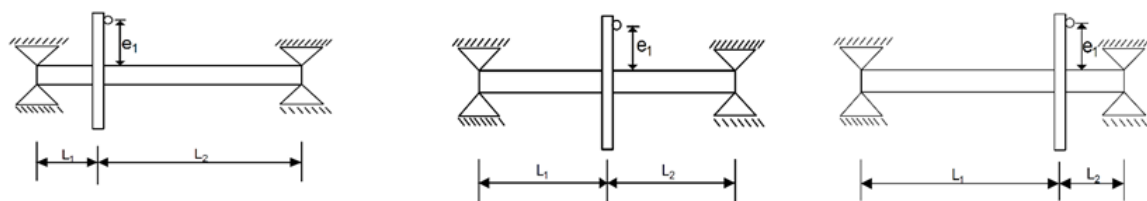

Figure 6: Schematic representation of the experimental set up (with unbalance fault)

The experimental verification for the Unbalance Identification of mass on a shaft with single plane and two eccentricity location has been performed on a Machine Fault Simulator available at Central mechanical Engineering Research Institute (CSIR-CMERI) in Durgapur.

A rigid shaft considered to be massless is mounted between two roller bearings. The distance between the two bearings is L_1+L_2, which is 60cm. This shaft is connected to a Variable Frequency Drive (VFD) motor by a flexible coupling. To measure the vibration in X-Direction and Y-Direction at the two bearings, four accelerometers are connected; two in each bearing. The weight of the disc is 653 gram (M_1). The position of the disc is varied in three different locations: (i) 15 cm from left bearing (ii) 30cm from left bearing which is the mid position on the shaft (iii) 45 cm from left bearing. Initially no unbalance mass was attached in order to get the no fault readings. Three unbalance masses of 8 gram (m_1), 12 gram (m_2) and 16 gram (m_3) are attached subsequently to the disc at eccentricities 6.85cm (e_1) and 6.85cm (e_2) separately one by one. Then the shaft is rotated at rpm 300, 600, 900, 1200 and 1500; and simultaneously the vibration readings (RMS values) and their phase values in x and y-direction at the two bearings were noted down. Artificial Neural Networking Techniques with varying training algorithmshave been used to determine the unbalance plane of vibration.

Mass Unbalance: The unbalance masses used are 8 gram, 12 gram and 16 gram which are shown in the figures below.

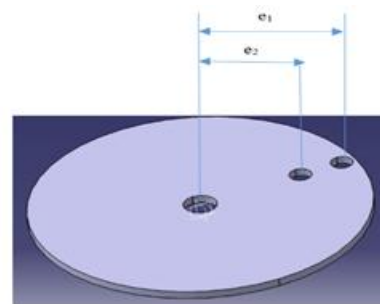|		
Fig 7	**Fig 8**	**Fig 9**

Fig 7: Unbalance mass of 8gram attached to the rotating system; **Fig 8:** Unbalance mass of 10gram attached to the rotating system; **Fig 9:** Unbalance mass of 8gram attached to the rotating system

Eccentricity:

All rotors have some eccentricity. Eccentricity is present when geometrical centre of the rotor and the mass centre do not coincide along their length. In the present case, the disc is considered absolutely balanced where the Geometrical Centre of the disc coincides with the Centre of the Gravity of the disc. In the current research work eccentricity is the distance between the Geometrical Centre (Centre of rotation) and the points where the unbalance mass is to be attached. There are two locations at a distance of 6.85cm from the centre of rotation (e_1) and at a distance of 4.85cm from the centre of rotation of the disc (e_2).

Fig 10: The rotating disc	**Fig 11:** Schematic representation of rotating disc

Plane of Unbalance:
The Figure 13, Figure 14 and Figure 15 shows the different position of the rotating disc placed on the shaft (left, centre and right respectively).
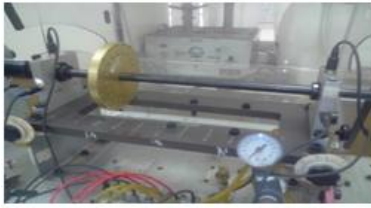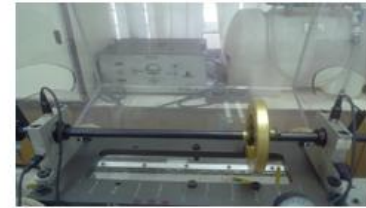
| **Fig 13** | **Fig 14** | **Fig 15** |

The design of experiment (Table 2) is based on the maximum possible combination of Unbalance mass (m), Eccentricity (e), Plane of unbalance (p) and the RPM (r) values. The table (Table 1) below provides the maximum and minimum values the independent parameters/input to the system.

Table 1: Independent/Input parameters and their levels

Serial No	Independent /Input Parameters	Minimum Level	Maximum Level
1	Unbalance Mass (M)	8gram	16gram
2	Eccentricity (E)	4.85cm	6.85cm
3	Plane Of Unbalance (P)	15cm (Measured From Left Bearing)	45cm (Measured From Left Bearing)
4	Revolutions Per Minute (Rpm) (R)	300	1500

Table 2: Design of Experiment

Set	Experimental Codes	Unbalance Mass (In Gram)	Eccentricity (In Cm)	Location Of Unbalance Plane (In Cm) *(From Left Bearing)*
1	Nfl	0	0	15
2	Nfc	0	0	30
3	Nfr	0	0	45
4	L8e2	8	4.85	15
5	C8e2	8	4.85	30
6	R8e2	8	4.85	45
7	L8e1	8	6.85	15
8	C8e1	8	6.85	30
9	R8e1	8	6.85	45
10	L12e2	12	4.85	15
11	C12e2	12	4.85	30
12	R12e2	12	4.85	45
13	L12e1	12	6.85	15
14	C12e1	12	6.85	30
15	R12e1	12	6.85	45
16	L16e2	16	4.85	15
17	C16e2	16	4.85	30
18	R16e2	16	4.85	45
19	L16e1	16	6.85	15
20	C16e1	16	6.85	30
21	R16e1	16	6.85	45

The design of experiment as mentioned in the table 2 has been performed for 300, 600, 900, 1200 and 1500 RPM`s. In total there are 105 set of experiments.

2.2 Indicators Used In Experiment :
NFC: No fault disc at Centre,**NFL**: No fault disc at Left position,**NFR**: No fault disc at Right position
The number succeeding NFC, NFL, NFR represents the rpm at which the disc is rotating without any unbalance mass attached. With unbalance mass attached, the experimental code is written in the following format as mentioned below one after the other.
Position of Rotating Disc (p) ⟶ Unbalance Mass (m) ⟶ Eccentricity (e) ⟶ Revolutions Per Minute (RPM) (r)
For example:C16e11500 represents the rotating disc placed at centre of the shaft with mass unbalance of 16gram placed at an eccentricity $e_1$rotated at 1500 RPM. It is similar for rest of the experimental cases.

III.   Results And Discussion:
Polar Plot Analysis
A polar plot displays data in polar coordinates, which enables you to see phase changes in the range of zero to 360 degrees. The polar plot zero degree point always is located at the angular position of a transducer. You can
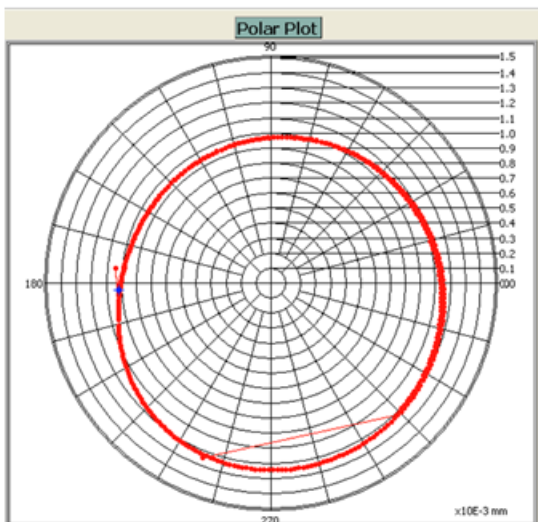
compare data from orthogonally-mounted proximity probe pairs with a polar plot. Fig16-23 depicts the polar plots for a no fault case and a faulty case with 16 gram unbalance mass placed on the disc at eccentricity $e_1$located at the centre of the shaft.
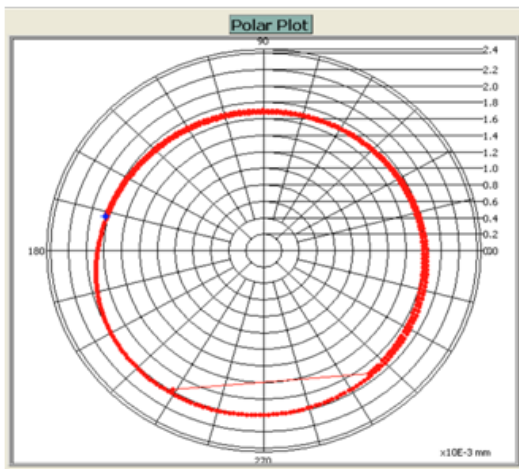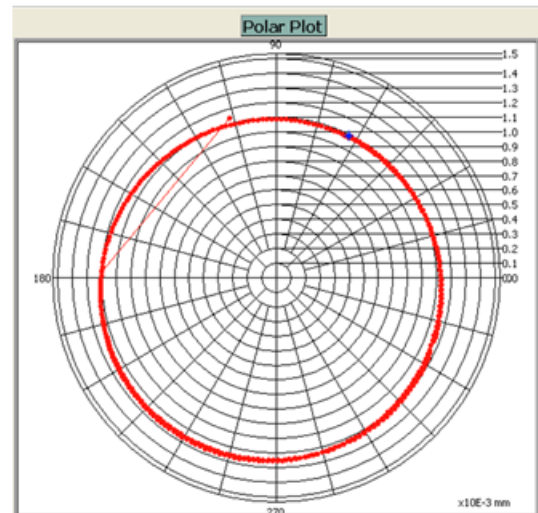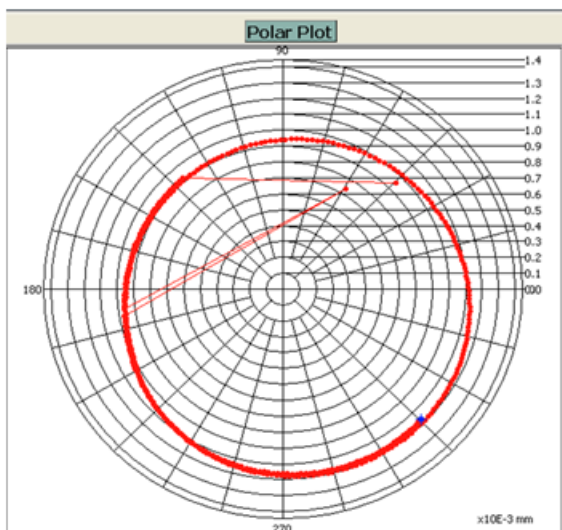

Fig 16: Polar Plot for NFC1500 (Ch-2)
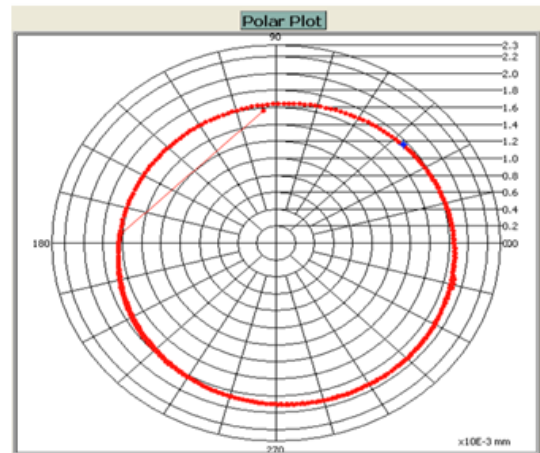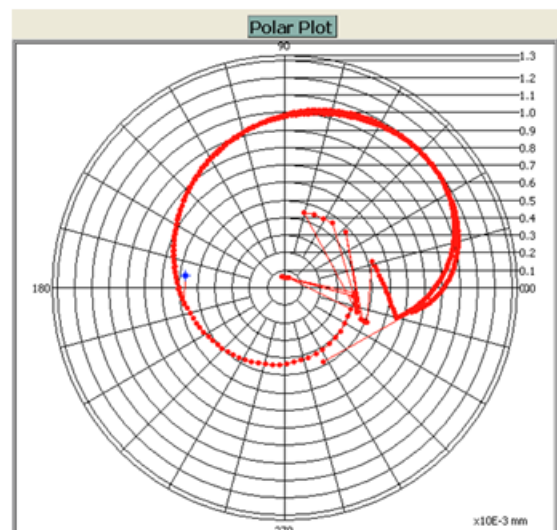

Fig 17: Polar Plot for C16E11500 (Ch-2)

Fig 18: Polar Plot for NFC1500 (Ch-3)

Fig 19: Polar Plot for C16E11500 (Ch-3)

Fig 20: Polar Plot for NFC1500 (Ch-7)

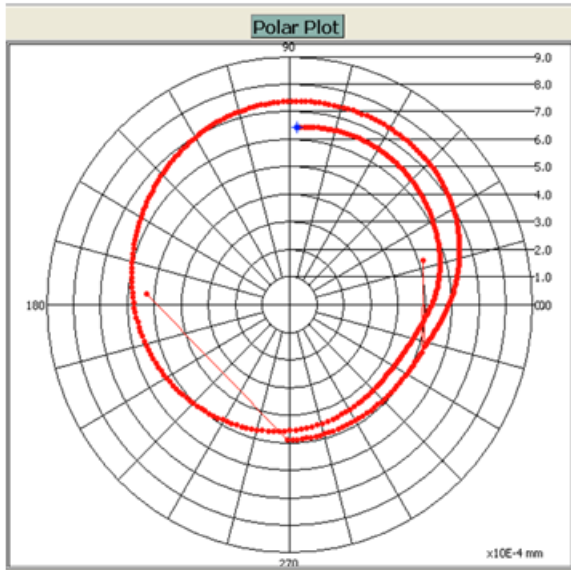**Fig 21:** Polar Plot for C16E11500 (Ch-7)
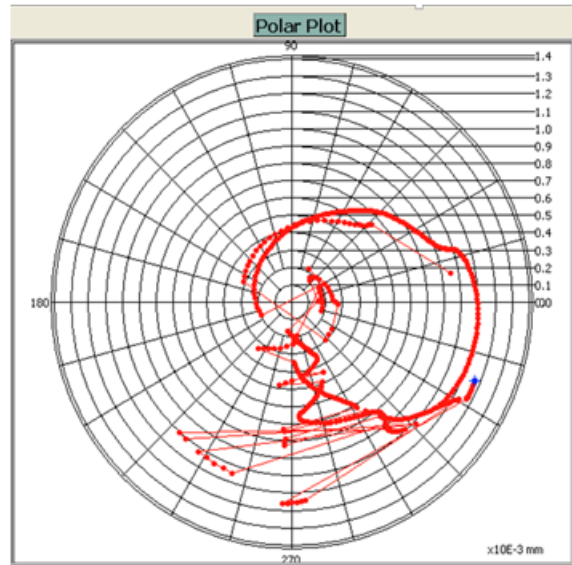
Fig 22: Polar Plot for NFC1500 (Ch-8)   **Fig 23:** Polar Plot for C16E11500 (Ch-8)

Table 3: Amplitude and Phase values from Polar Plot Analysis

	Left Bearing X-Axis (Channel-2)		Right Bearing X-Axis (Channel-3)		Left Bearing Y-Axis (Channel-7)		Right Bearing Y-Axis (Channel-8)	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
No Fault Case	1.54E-3	166.79	1.02E-3	182.66	1.18E-3	315.49	6.49E-4	87.70
C16E11500	1.77E-3	41.27	1.10E-3	63.13	2.73E-3	172.94	1.18E-3	337.11

From the polar plot analysis, it is evident that there exists a phase difference of 90degrees for unbalance fault in each direction of the bearings. Proximity probes like Channel-2, Channel-7, Channel3 and Channel 8 have been set up to measure the vibrations in Left Bearing X, Left Bearing Y , Right Bearing X and Right Bearing Y direction respectively. The phase difference for Channel-2 and Channel -3 are 125.52 and 119.53 degree respectively which can be considered to be very close to each other. There is a little more difference in values for Channel-7 and Channel-8 due to experimental error which is within the limits of acceptance.

IV.   Orbit Plot Analysis
The ellipticity of the filtered orbit, as well as the amplitude and the inclination angle of the major axis of the orbit, are parameters whose analysis can provide important diagnostic information
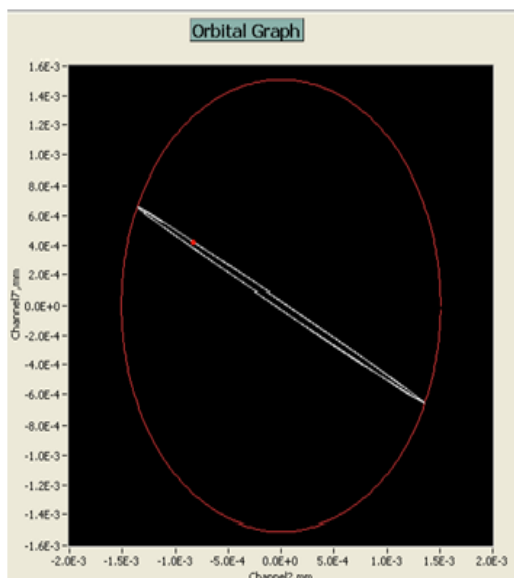

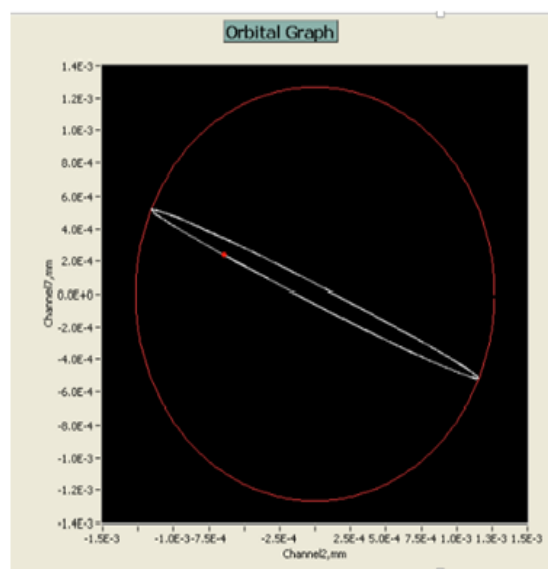**Fig 24:** Orbit Plot for Ch-2 & 7 (No fault case)   **Fig 25:** Orbit Plot for Ch-2 &7 (C16E11500)
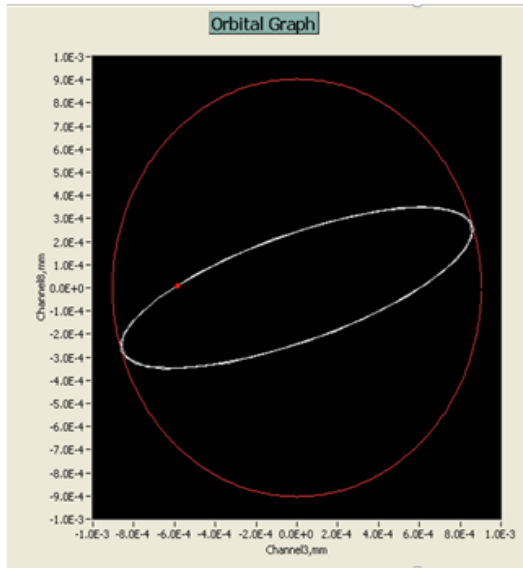
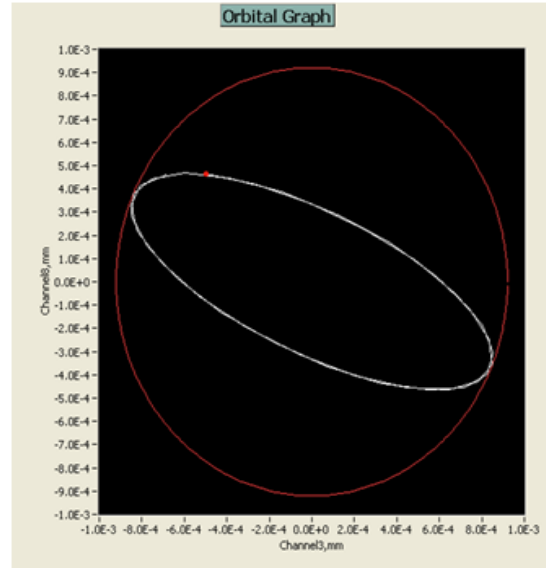**Fig 26**: Orbit Plot for Ch-3 & 8 (No fault case)   **Fig 27:** Orbit Plot for Ch-3 &8 (C16E11500)

Table 4: Overall values from Orbit Plot Analysis

	Left Bearing X-Axis (Channel-2) (Overall values)	Left Bearing Y-Axis (Channel-7) (Overall Values)	Right Bearing X-Axis (Channel-3) (Overall Values)	Right Bearing Y-Axis (Channel-8) (Overall Values)
No Fault Case	.00231	.00104	.00171	.0008
C16E11500	.00271	.00131	.00173	.000932

From the orbit plot analysis, it is evident that the area of the ellipse for unbalance fault case ismore than that of the no fault case. From Table 4 , it can be seen that the overall values in case of the unbalance fault case is more as compared to its no fault case. From the shape of the curve in the orbit plot, the type of fault can be determined, which in this case is unbalance fault as because the plot is elliptical. Different shapes of plot indicates various faults in the rotating system.

V.   Conclusion

A comparative polar and orbit plot analysis has been done for no fault and faulty case. Similarly, polar and orbit plots can be drawn for different other faults like misalignment, bearing faults etc with more than one disc mounted on the shaft and more than one unbalance mass attached to the system.

Acknowledgement

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