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Gear wear process monitoring using acoustic signals

GEAR WEAR PROCESS MONITORING USING ACOUSTIC SIGNALS

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Abstract

Airborne acoustic signals contain valuable information from machines and can be detected remotely for condition monitoring. However, the signal is often seriously contaminated by various noises from the environment as well as nearby machines. This paper presents an acoustic based method of monitoring a two stage helical gearbox, a common power transmission system used in various industries. A single microphone is employed to measure the acoustics of the gearbox undergoing a run-to-failure test. To suppress the background noise and interferences from nearby machines a modulation signal bispectrum (MSB) analysis is applied to the signal. It is shown that the analysis allows the meshing frequency components and the associated shaft modulating components to be captured more accurately to set up a clear monitoring trend to indicate the tooth wear of the gears under test. The results demonstrate that acoustic signals in conjunction with efficient signal processing methods provide an effective monitoring of the gear transmission process.

Keywords: Acoustic signals, Modulation signal bispectrum, Gear Transmission, Condition monitoring

1. Introduction

Gears have long been used as a means of power transmission in many industrial applications such as terrestrial gearboxes and power generators [12]. Significant evidence from industry shows that gear failure rates frequently result in major disruption and losses. To improve operational and safety effectiveness, condition monitoring and fault identification are common practices in modern industries.

Vibration based method is the mainstream techniques of CM. However, it is often difficult to locate an appreciate place for installing accelerometers. On the other hand, as the response of structural vibration, airborne sound can be picked up by microphones distant from the objects, which makes it much easier to be implemented in situ. Moreover, microphones generally have wider frequency response, ranging from 20Hz to 20 kHz, which can include a great deal and detailed information in this bandwidth. Acoustic signals from one microphone can include information from different components of a machine. It means that only a couple of sensors are required to monitoring the whole system, whereas many accelerometers are needed monitoring different components [13, 14]

However, airborne acoustic signals may need to be pre-processed more intensively to suppress background noise and remove interferences for improving the signal to noise ratio (SNR) of interesting sources and extracting the characteristics of the sound sources from the noise signals for fault diagnosis. It has shown that wavelet transforms [1], independent component analysis (ICA) [2], and adaptive filtering techniques [3] are effective to process the non-stationary acoustic signals in monitoring engine problems with combustion, abnormal valves and fuel injectors of diesel engines.

Compared with diesel engines, the acoustic signals from a gear transmission may be more stationary and have more distinctive modulation. In the general review paper, many different signal processing techniques are investigated for processing such vibration data [4] in the time domain, frequency domain and time-frequency domain for monitoring gearbox. Among them novel methods such as cyclo-stationary analysis [5] and empirical mode decomposition method (EMD) [6] are of particular interesting as they focus on characterising the modulation nature in the vibration data which is the critical feature of the vibration.

On the other hand, higher order spectra (HOS) are useful signal processing tools due to its unique properties nonlinear system identification, phase information retention and Gaussian noise elimination. The application of HOS techniques in condition monitoring has been reported in [7]. Recently, Gu et al [8 examined the performance of a modulation signal bispectrum (MSB), an extension of conventional bispectrum, and showed that it is more efficient in characterising the weak modulation of electrical signals from compressors and gearboxes for diagnosing different common faults. As the vibro-acoustic signals has the modulation effects, this study will examine the use of MSB to extract the modulation from acoustic signals of gearbox for developing more accurate approaches to monitoring gearbox conditions.

2. Gearbox Vibro-Acoustics

2.1 Acoustic signal contamination

The vibration source will firstly show as the structural vibration response of the gearbox case through the effect of the transfer function derived from shafts and bearings. Usually, there are a number of resonances in the frequency range of interest due to both the transfer paths and the case dynamic characteristics. These resonances cause the vibration responses and their associated acoustics to have nonlinear connections to the faults. The resonance effect produces good signal to noise ratio data but it needs to be carefully analysed in using the signal amplitudes to explain the fault severity. It may give higher amplitudes in some frequency ranges compared with those in which there are no resonances.

Airborne sound is a sequence of pressure waves that propagate through a compressible media, and during its propagation the sound waves are reflected, as well as refracted and attenuated. Acoustics in typical industrial machinery undergo many thousands of reflections before eventual decaying below limits of detectability [11]. As such, the effect of room reflection on the sound power levels in the vicinity of a small machine situated in a relatively large room would be expected to be small [**Error! Reference source not found.**]. In a workshop, testing is done in a natural environment of a large room, with reflecting surfaces. However, if the sound sources are located in an enclosed space, the reflection caused by the boundary of the enclosed space will affect the basic characteristics of the sound source, and increase the difficulties for fault diagnosis by analysing airborne sound signals.

Although the resonance modes of the room were not considered as a reverberant chamber, the sound waves used, especially in the low frequency range, may be inaccurate and misleading. Great care has to be taken in interpreting the information content [15]. Also interference is generated by other signals (in other circuits or, more likely, in the same circuit), so it may give rise to artificial effects not related to the noise source under investigation.

2.2 Vibro-acoustic Sources of Gear Transmission

For a healthy gear set, ignoring manufacturing errors but including tooth deformation due to loads, the vibro-acoustic sources $x_h(t)$ will be dominated by the meshing frequency components and can be approximated in the following form [9, 10]:

$$x_h(t) = \sum_{k=0}^{K} A_k \cos(2\pi k f_m t + \varphi_k) + w(t) \qquad (1)$$

where $f_m = z f_r$ is the meshing frequency which is the multiplication of tooth number z and the shaft rotating frequencyf_r, A_k and φ_k are the amplitude and respectively phase of the k^{th} harmonic, K is the number of meshing frequency harmonics of interest, and $w(t)$ is the noise which is assumed to have a normal distribution.

However, there are inevitable manufacturing errors such as errors in tooth spacing, tooth profile, alignment, as well as gear faults including tooth wear, cracks and damages which all alter the meshing stiffness and cause variations in both amplitude and phase of the tooth meshing vibrations[16]. The variation in the amplitude and can be approximated by modulating functions $\mathrm{a_k}(\mathrm{t})$ and $\varphi_{\mathrm{k}}(\mathrm{t})$ respectively which are also periodic with the shaft frequency and can be written as:

$$a(t) = \sum_{k=0}^{\infty} A_k \, cos(2\pi k f_r t + \alpha_k) \tag{2}$$

$$\varphi(t) = \sum_{k=0}^{\infty} B_k \, cos(2\pi k f_r t + \beta_k) \tag{3}$$

Substituting these modulating components into Equation (1) yields the overall vibro-acoustic source expression:

$$x(t) = \sum_{k=0}^{K} A_k [1 + a_k(t)] \cos\big(2\pi k f_m t + \varphi_k + \varphi_k(t)\big) + w(t) \tag{4}$$

The form of equation (4) emphasises that the source contains a complicated modulation process due to the presence of errors in the gear system. Obviously gear faults such as tooth breakage and wear will alter the characteristics of modulation further. Therefore it is critical to characterise the modulation appropriately in order to differentiate faults from the manufacturing errors and noise.

3. Modulation Signal Bispectrum

According to the definition of MSB in the frequency domain, the meshing frequency f_m and sideband f_r in an acoustic signal can be correlated [8] as

$$B_{MS}(f_r, f_m) = E[X(f_r + f_s)X(f_r - f_s)X^*(f_m)X^*(f_m)] \tag{5}$$

where $X^*(f)$ is the complex conjugate of the Fourier transform $X(f)$ of acoustic signal $x(t)$; and $E[\,]$ is the statistical expectation operator. And the power spectrum of $x(t)$ is

$$PS(f_m) = E[X(f_m)X^*(f_m)]$$

Equation(5) shows that through the operation of vector average in the frequency domain, MSB can extract the combination of components at the meshing frequency, the lower sideband and the higher sideband. In the meantime, other components including random noise and interfering components that are not meet the phase relationship will be suppressed significantly. In this way the modulation effects in acoustic signal can be represented more accurately and reliably.

To examine the modulating components along, rather than that of the combination with the meshing component, a MSB sideband estimator (MSB-SE) can be used according to (6)

$$B_{MS}^{SE}(f_r, f_m) = E[X(f_r + f_s)X(f_r - f_s)X^*(f_m)X^*(f_m)/|X(f_m)|^2] \tag{6}$$

Because of the magnitude in equation (6) is normalised the magnitude of the MSB-SE is only the products of the lower and upper sideband, which reflects more the modulating component from faults.

In addition, MSB coherence (MSBC) defined in Equation (7) can be based on to estimate the influences of random components

$$b^2{}_{MS}(f_r\,, f_m) = \frac{|\;B_{MS}(f_r, f_m)|^2}{PS(f_m)E[|X(f_m + f_r)(f_m - f_r)|^2]} \tag{7}$$

MSB coherence has boundary [0 1]. 1 means that MSB magnitude from true modulation effects. On other hand a zero value means that the MSB magnitude is mainly from random noise influences. Thus other values of MSBC will indicate the reliability of MSB peaks. In addition, for a given measurement environment, the noise is relative the same. The increase of MSBC can be an indicator of modulation degree and used for detecting the presence of modulation

4. Experiment Facilities and Procedure

Fig. 1 shows the gearbox test rig of the test facility employed to examine gearbox faults though acoustic measurements. The system consists of a 3-phase induction motor, a two-stage helical gearbox, flexible couplings and a DC motor which acts as a mechanical load. The induction motor is rated at 11kW at 1470 rpm and controlled though a variable speed drive to operate under different operating conditions. The gearbox under test is also rated at 11kW at 1470 rpm. The technical specification of the helical gearbox is detailed in Table 1. In general the rig is sufficiently large to represent many industrial applications for evaluating the performance of acoustic signal based condition monitoring.

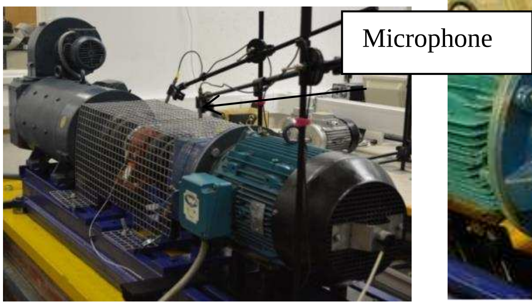

Fig 1. Photograph of the experimental test rig

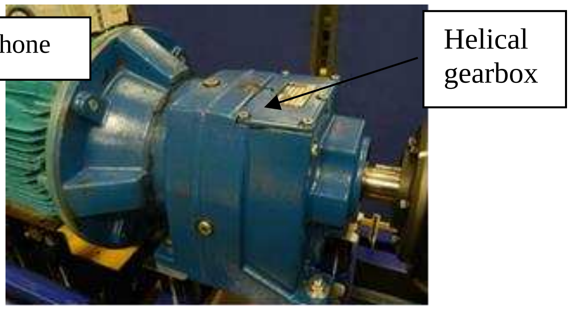

Fig 2. Photo of Helical gearbox

Table 1. Specification of Two-Stage Helical Gearbox

Gear Parameters	1st Stage	2nd Stage
Number of teeth	58/47	13/59
Shaft speed	fr1=24.5Hz	fr2=30.23 and fr3=6.66
Meshing frequency	fm1=1416.36Hz	fm2=391.76Hz

Acoustic signals are measured by using a microphone system consisting of an electrets microphone, a preamplifier and a four channel portable ADC device. Table2 shows the specification for the system. During the test, a data length of 30 second is recorded for the speed channel and acoustic channel.

Table 2. Microphone Specification

Model	Preamplifier YG201	Microphone CHZ-211	USB Data Acquisition
Frequency rang	10Hz~110kHz (±0.2dB)	6.3Hz~20kHz (±2dB)	96kHz sampling rate
Sensitivity or gain	1	26±1.5dB (50mV/Pa)	24bit sensitivity
Temperature range	-40°C~+85°C	-40°C~+80°C	4 channel

To show the capability of acoustic signal based monitoring, a run-to-failure test was performed based on the helical gearbox. To speed up failure, the tooth width of pinion at the input shaft induced is removed to increase local stress for an early failure. However, as the high overlap ratio the gear can still maintain operates with notable reduction of performance. While the gearbox operates continuously during the test the gearbox was being monitored on-line by vibration, angular speed and instantaneous annular speed measurements. The test was terminated at the time instant when the sideband of instantaneous current signals shows a significant increase. During the course of the test, acoustic data was also collected at an interval of about 50 minutes, depending on the availability of the measurement system, and processed off line to identify an effective signal processing method to match the monitoring capability of other measurements.

5. Results and Discussion

The recorded acoustic data is processed using MSB and power spectrum methods. Both of them are calculated with 80 times of average and frequency resolution of xx.

5.1 Characteristics of Gearbox Acoustics under Different Loads

Fig 3 shows MSB and its corresponding MSBC results under different loads at an initial operation phases of 65.8hours for the first two meshing frequencies. In the graph, f2 is for the carrier frequencies such as meshing frequency while f1 is for the modulating components such as that of shaft rotating frequencies including: fr1, fr2 and fr3. It can be seen that MSB magnitudes at fr1 is the predominant components on both the 1st and the 2nd meshing frequencies. In the meantime, the magnitude at fr2 and fr3 are also visible, showing that MSB magnitude provides detailed information about the modulation effect of gear transmission due to the inherent manufacture errors. In addition, all these characteristic peaks are fully supported by MSBC peaks, showing Fig.3 (b1) and (b2).

Moreover, it is observed that MSB magnitudes at fr1 and fr2 on the second harmonics increase with the load, which is consistent with that the modulation amplitude increases with loads due to more deformation of tooth profile at higher loads. On the other hand, the MSB amplitudes on the 1st meshing frequency show an adverse connection to the load. This may be because of nonlinear effects of the vibro-acoustic transmission paths and more interfering influences from other low frequency sources. In addition, MSB amplitudes at fr3 also show more distinctive peaks on the 1st meshing frequency, which may cause influences on the diagnosis accuracy of the fault from the gear set at fr1 and fr2.

Therefore the MSB results on the 2nd harmonic component of the meshing frequency are based on to characterise the dynamics of gear transmission and hence to develop more reliable features for monitoring any changes caused by abnormal gear transmission.

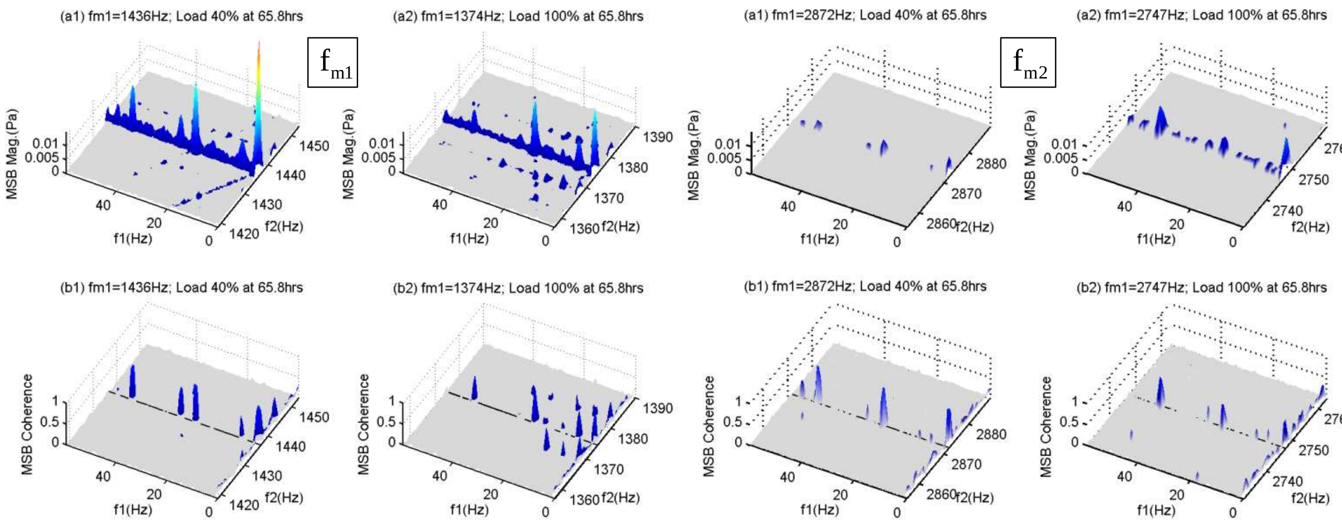

Fig 3. MSB and MSBC around different meshing frequencies and under different loads

5.2 MSB based Detection and Diagnosis

To confirm the detection and diagnosis performance of the selected carrier frequency band around fm2, MSB results are examined at different time instants. Fig. 3 shows MSB and MSBC results around fm2 for 5 different advance time instants. Bothe MSB and MSBC exhibits two general features:

- The magnitudes is increasing with time advances; and
- The number of distinctive magnitudes is becoming higher with time advances.

These two critical features demonstrate that the modulation effects increase as the gear condition is becoming deterioration. As operating time advances, the gear tooth profile will be damaged gradually. This will lead to more vibrations and hence acoustics at frequencies relating to the gearing meshing process. In fact, when the gear is inspected after the test it has found that the tooth surfaces on both the pinion and gear show clear markers. Therefore, it has shown that acoustic data associated with MSB analysis is effective to detect and diagnose the gear condition.

In addition, it can be seen that MSB results at time instant of 406 hours is slightly deviated from the general features. It has less amplitude in the carrier frequency range between 2700Hz and 2750Hz. This may show that the acoustic signals may be interrupted by background noise such as communications of the test operators or other unknown factors. Nevertheless the main features of modulation effect are still distinctively shown in the results.

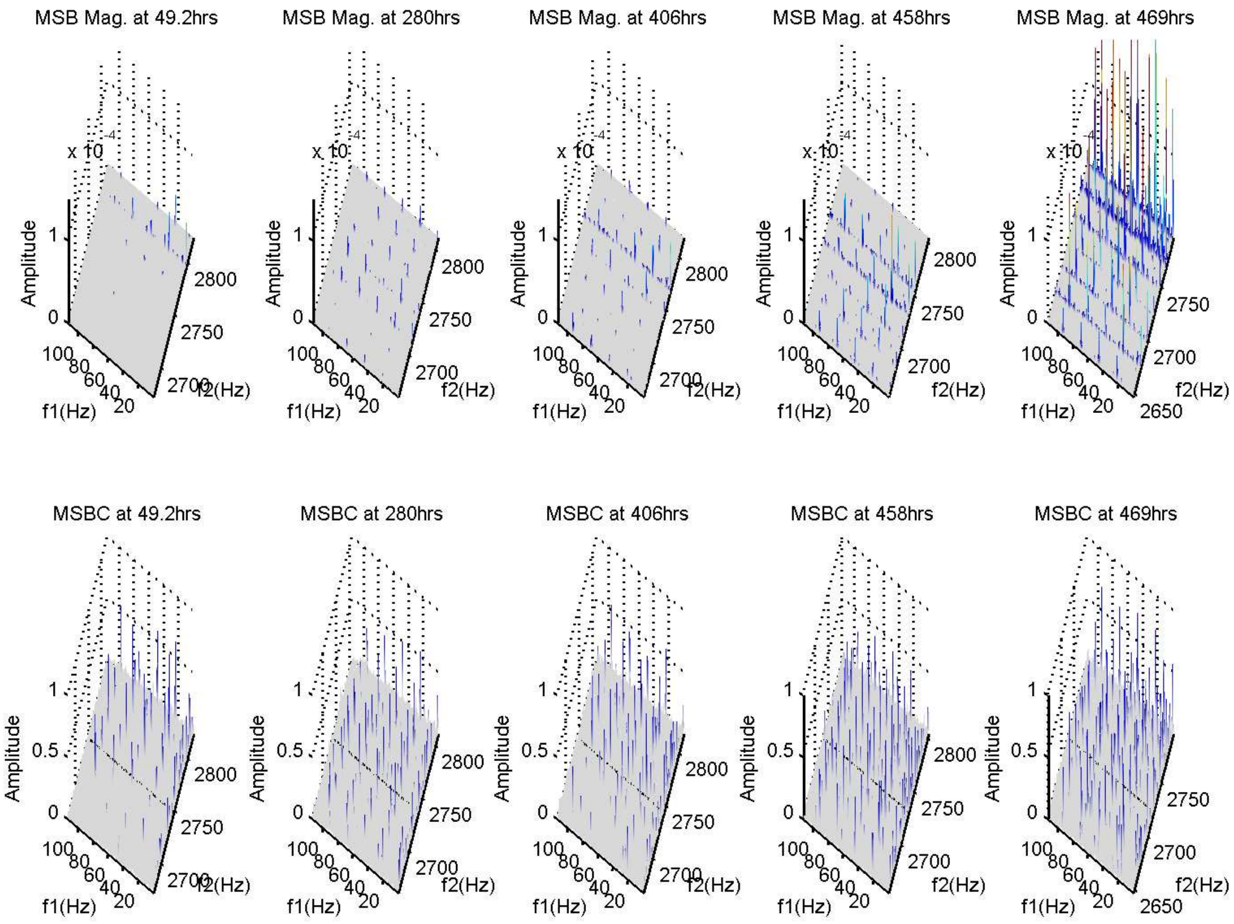

Fig4 . MSB and MSBC for gearbox deterioration in successive time instants under high load

5.3 Monitoring Trend

To evaluate the performance of MSB analysis based acoustic monitoring, three MSB trends are developed based on features observed in the frequency range. The first one is the entropy of MSBC for describing the increase of coherence peaks. The second one is the average magnitude of MSB and the third is the average magnitude of MSB-SE. In addition, the average amplitude of power spectrum is also calculated for performance comparison. Fig. 4 shows the trend variation over the testing period. In general they all show an increase trend with the operating time. However, the trend of power spectrum and entropy exhibit large variance because they contain the influences of random noise. On the other hand although the trend of MSB-SE has less variance, it exhibits little change in the middle period of the operating. It shows that the sideband changes of MSB-SE show little indication of the deterioration of gear conditions in the period.

However, MSB trend, which is a combination of both the sidebands and the meshing frequency components, exhibits less variance and early indication. Thus it can be used for monitoring and predicting the fault advances more accurately. This proves that the MSB analysis is effective in extracting modulation characteristics of gear deterioration and excluding the noise influences on acoustic signals.

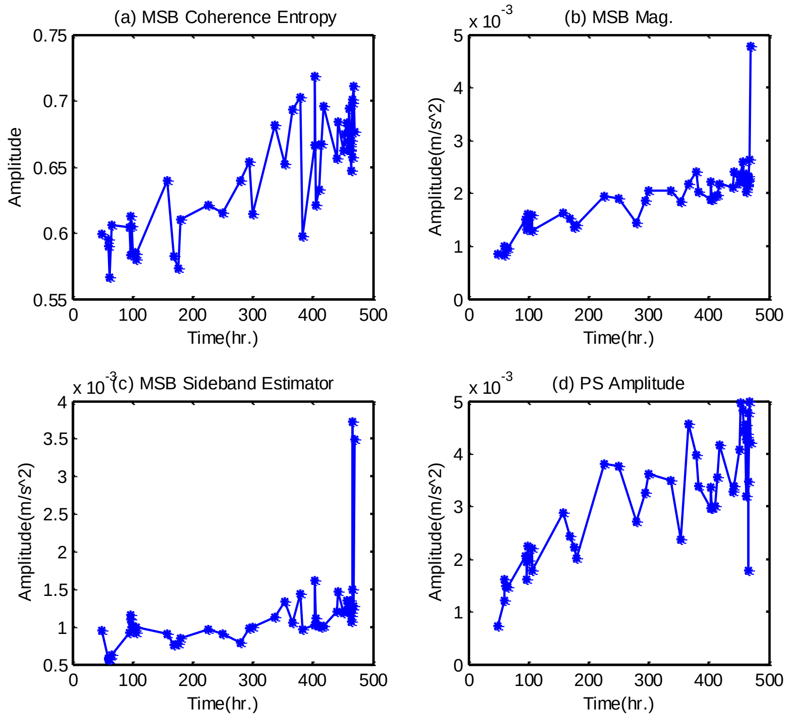

Fig5 Monitoring trends of MSBC, MSB, MSB-SE and PS for gearbox deterioration

6. Conclusion

This study shows that the acoustic signals contain the information of gearbox deterioration process. However, as the signals can be distorted by various factors including background random noise and interferences from nearby acoustic sources, MSB analysis is one of effective methods which are highly selective to the modulation characteristics of gearbox deterioration by suppressing such noise influences.

The results of gearbox deterioration monitoring shows that the monitoring feature need to be developed based on the frequency range around the 2nd harmonic components of the meshing frequency. Moreover, MSB magnitude which includes the magnitude changes at both the sidebands and meshing frequency has to be used to monitor the process.

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