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Gear Crack Detection Using Residual Signal and Empirical Mode Decomposition

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Diagnosis of gearbox defects at an early stage is very important to avoid catastrophic failures. This article presents experimental results of tests made to evaluate the cracks of the cylindrical gears of a transfer case under advanced test conditions. For the diagnosis of a gearbox, various signal processing techniques are mainly used for the vibration study of the gears, such as: Fast Fourier Transform, synchronous time average, and time-based wavelet transformation, etc. Various methods can be found in the literature which can be used to calculate the residual signal (RS), however, in this paper, we suggest a new method combined empirical mode decomposition (EMD) technique with RS for detection of the crack gear. In order to extract the associated defect characteristics of the transfer box vibration signals, the EMD has been performed. The results show the effectiveness of the EMD method in the evaluation of tooth cracking in spur gears. This effectiveness can be proved by the obtained results of the experimental tests, which were presented and carried out on a test rig equipped with a transfer box.

Keywords: Crack defect, gear, vibration signal, residual signal, empirical mode decomposition.

1. Introduction

The transmission of movements by using gearboxes, is existing in almost all rotating machinery. It can be found in many industrial sectors such as gearboxes of vehicles, aircraft engines and wind turbines. Gear defects indicate that the tooth cracking may occur in the gears production phase [1], or during the operating phase under severe operating conditions, such as excessive service load, inappropriate operating conditions, or simply fatigue [2, 3]. Different fault diagnosis methods have been developed and used to detect and diagnose gear faults. One of the principal tools for diagnosing gear faults is the vibration analysis [4, 5]. The role of vibration health monitoring is to detect the deterioration due to fault propagation before the occurrence of sudden breakage. Early detection allows proper scheduled shutdown to prevent catastrophic failures, and consequently results in a safer operation and higher cost savings [6, 7]. The defects in their nature are localized transient events and cause a distribution of the energy of the vibration signal. To treat nonstationary signals, techniques such as time-frequency distributions [8], wavelets and higher order statistics [9], Cepstrum analysis, envelope analysis and higher-order statistics have brought more attention and gained good acceptance.

The most undesirable damage that can occur in gear units is a crack in the tooth root, as it often makes gear unit operation impossible [10]. The changes in tooth stiffness caused by a fatigue crack in the tooth root are of high significance [11], as the dynamic response of a damaged gear unit differs from the one of an undamaged tooth. Due to the importance of this phenomenon, many studies have been presented on gear crack detection. Andrade et al. [12] introduced a new technique for early identification of spur gear tooth fatigue cracks, namely Kolmogorov-Smirnov test. While, Baydar and Ball [13] used the Wigner–Ville distribution to identify gear crack.

The variable amplitude Fourier series (VAFS) is proposed by Yuan and Cia [14], this method is based on an improvement of the traditional Fourier series analysis, and comes from the analysis of the gear meshing vibration signal model. Belsak and Flasker [15] and Yu et al. [16] performed time frequency analysis and time–frequency entropy based on Hilbert–Huang transform. The analysis results indicate that the vibration analysis is efficient and feasible for gear crack detection. Afterwards, Loutridis [17] applied the energy-based features for gear fault diagnosis, and the predictions are proposed. The instantaneous energy density is shown to obtain high values when defected teeth are engaged. Barszcz and Randal [18] presented the application of the spectral kurtosis technique for detection of a tooth crack in the planetary gear of a wind turbine. This method was able to detect the existence of the tooth crack several weeks before the gear failure. Recently, Wavelet method [19, 20] employed to detect gear crack. On the other side, Wang [21] proposed K-nearest neighbors based methods for identification of different gear crack levels under different motor speeds and loads.

In the quest of a precise localization of time and frequency, the empirical mode decomposition system (EMD), suggested by Huang et al. [22], it offers different approaches to the treatment of time series. The method has been developed and widely used [5, 23–25]. EMD is a time-adaptive decomposition operation of the signal, which decomposes the signal into a set of complete, and almost orthogonal components, named as intrinsic mode function (IMF). IMFs are almost mono components and represent simple oscillatory modes embedded in the signal [26]. Nowadays, the EMD method is applied in several research areas, such as ocean and seismic engineering, nuclear physics, biomedical diagnosis, image processing and structural testing [27].

According to our knowledge concluded from the literature, most of experimental studies considering big loads for detection of crack gear in rotating machinery. On the other hand, such machines can also work with light charges which make the detection of these faults much harder than usual, therefore, and in order to confirm the viability of our new method combining empirical mode decomposition technique with residual signal [28] for detection of crack gear with light loads.

2. Materials and Methods

2.1. *Signal-Processing Technique*

2.1.1. *Empirical Mode Decomposition*

By the EMD technique, the vibration signal $x(t)$ is automatically decomposed into the integrated mode function which is a set of limited band functions. Here, only the main steps of this method were cited, and for a complete summary refer to [22]. Each IMF should meet two conditions:

1. In the full signal, the number of extrema (extreme values) and zero crossings shall be equal or at most different by one.
2. The value of the moving average envelope defined by local maxima and the envelope defined by local minima are zero.

The decomposed signal may be presented as:

$$x(t) = \sum_{n=1}^{N} \mathrm{IMF}_N(t) + r_n(t)\,, \tag{1}$$

where, $\mathrm{IMF}_N(t)$ symbolizes the n-th intrinsic mode function and $r_n(t)$ the residual component.

3. Residual Signal

The purpose of the residual signal given by Stewart [29] is to eliminate the components that occur at the base and the harmonics of the dental mesh frequency from the time average. The average of the time domain is based on obtaining a signal describing a revolution of the gear considered by averaging the vibration signal over a number of revolutions. It can be used to eliminate all components which are not synchronized to the tree, including noise. Then, the objective of obtaining the residual signal is to suppress the influence of noise and regular vibration components, and to illustrate the signal components generated by the damage due of the crack.

In this article, the proposed method based on EMD method shows that the residual signal is obtained by deleting some IMF representing the harmony of the mesh frequency of teeth, noise and regular signal.

The following steps represent the method:

1. Firstly, we decompose the signal into intrinsic mode functions, $\mathrm{IMF}_1, \ldots,$ IMF_N, by EMD algorithm, where n is the number of IMFs.
2. By applying the next equation, we consider the time synchronous average of each IMF:

$$\mathrm{IMF}_{TSA}(t) = \frac{1}{N} \sum_{i=0}^{z-1} \mathrm{IMF}(t + iT_e)\,, \tag{2}$$

   where T is a rotation period, and N is the number of periods.

3. We can calculate the residual of each IMF, using the following equation:

$$\mathrm{IMF}_{res}(t) = \mathrm{IMF}_{TSA}(t) - \frac{1}{z}\sum_{i=0}^{z-1} \mathrm{IMF}(t + iT_e)\,, \tag{3}$$

   where $\mathrm{IMF}_{res}(t)$ is the residual signal, $\mathrm{IMF}(t)$ is the vibration signal, T_e is the mesh period, while z is the number of teeth of the gear, and $\mathrm{IMF}_{TSA}(t)$ is the time synchronous average signal that can be calculated by the equation (2).

4. We calculate the residual signal by summing all the residual IMFs that have a Kurtosis superior to 3.

$$x_{res}(t) = \sum_{i=0}^{n} \mathrm{IMF}_{res}j(t)\,.\,, \tag{4}$$

5. In the last step, we calculate the Kurtosis of the residual signal to check if there are pulses in the residual signal.

Kurtosis is a parameter which measures the degree of peakedness of a distribution, and defines the signal shape as compared to the normal distribution. The Kurtosis value is associated with the distribution tail length [6, 30]. In practice, we need to install a phase reference (associated with resampling and interpolating techniques) or an encoder (for angle sampling) on each shaft. In fact, this is complicated and sometimes impossible to be accomplished. Check [31, 32] for further discussions of the synchronous averaging. In our tests, we used constant sampling rate (12.8 kHz). Knowing precisely the frequencies fr_1 and fr_2, we cut the signal in slices of length $T_1 = 1//f_{r1}$ and $T_1 = 1//f_{r2}$ respectively. If the slice number M begins with the m-th the sample, m is given so that $|mT_S - MT_1| \le T_S/2$, where $T_S = 1/f_S$ is the sampling period, so as to be as close as possible to the real synchronized averaging, as presented in Fig. 1, [33].

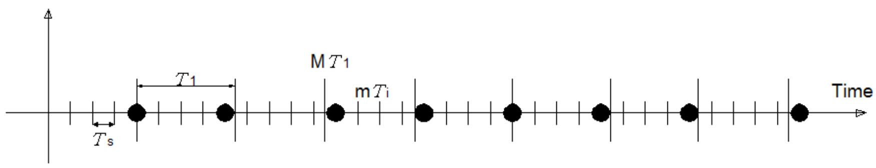


Figure 1 Synchronized averaging

3.1. *Experimental Set-Up*

For our tests, we used three pairs of spur gear-units: Two pairs with a fatigue crack, while the third without it. An accelerometer was fixed on the housing to measure directly the vibration signals of those three pair's gear-units (Fig. 2). Each gear unit was made of carburised spur gears. Additional data of the experimental setup are summarized in Tab. 1.

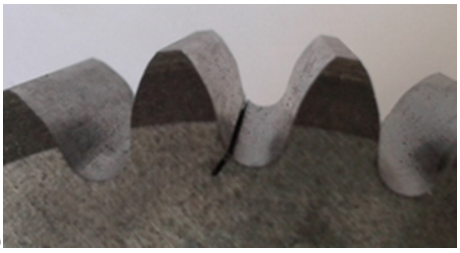
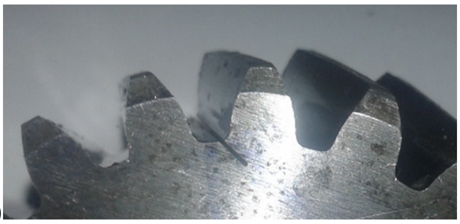
(a)

(b)


Figure 2 Details of gear damage for experiment: (F1) tooth crack from 20% and (F2) tooth crack from 40%

The experimental platform consists of a straight-tooth gearbox, a power supply unit with the data acquisition system, and necessary speed control electronics. Referring to Fig. 3, a 1.5kW DC machine rotates the wheel and the resistant torque is assured by a magnetic brake. The transmission ratio is $28/22 = 1.27$, which means that an increase in the rotational speed can be achieved. The output gear was artificially damaged with various deep cracks in the different levels.

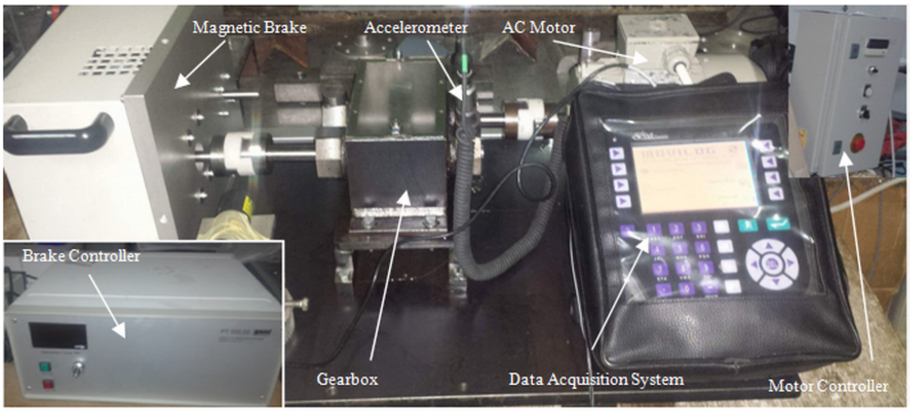


Figure 3 Experimental platform

3.1.1. *Generation of crack on pinion tooth*

Defective gears were obtained by introducing fatigue cracks into standard operating gears. For this purpose, a wire electro-erosion machine was used. The cut reproduced 0.3mm thick cracks in the tooth fillet position associated with the critical

Table 1 Important characteristics of the gears

	Gear 1	Gear 2
Tooth number N_G	28	22
Module m [mm]	3	
Pressure angle [deg]	20	
Mass moment of inertia J [kg m^2]	0.00101	0.00038
Face width F [mm]	27	
Backlash $2B$ [mm]	0.14	
Center distance [mm]	75	
Torque [Nm]	3.7	

stress [27]. Figure 2(a) and (b) shows the two different cuts of the cracks. For the two fatigue cracks (F1 = 20%, F2 = 40%), the cut covers the whole face of the tooth (25mm). For a complete description and details of the cut geometry and dimensions, refer to Tab. 2. Figure 2 illustrates the studied defects.

Table 2 Illustration of the crack cut geometry

gears	depth gears (mm)	width (mm)	thickness (mm)	angle (deg)
a	0 (00%)	25	0.3	45°
b	1.6 (20%)	25	0.3	45°
c	3.3 (40%)	25	0.3	45°

4. Results and Discussion

An EMD program is applied to signals in Matlab environment to receive data, in order to use its signal processing toolkits [34].

In this study, we used a single output shaft speed equal to 1200rpm and with two torques of 1.5 and 3Nm. In each test, the vibration was monitored online and the data were collected only after the signature model was stabilized. Examples of the results are described below.

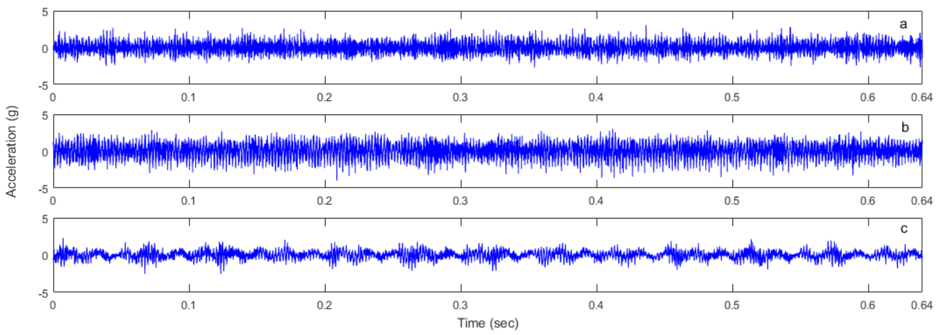


Figure 4 Time signal of gear for 1.5 Nm of load: (a) healthy gear (b) and (c) tooth crack from 20% and 40%

Figures 4 and 5 shows the time domain of acceleration signals from healthy gear and tooth crack from 20% and 40% for both load of 1.5 and 3Nm respectively. By

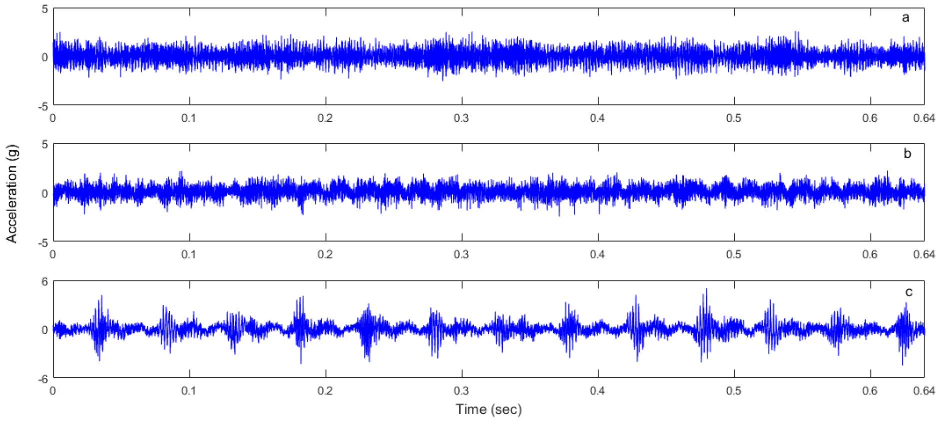


Figure 5 Time signal of gear for 3 Nm of load: (a) healthy gear (b) and (c) tooth crack from 20% and 40%

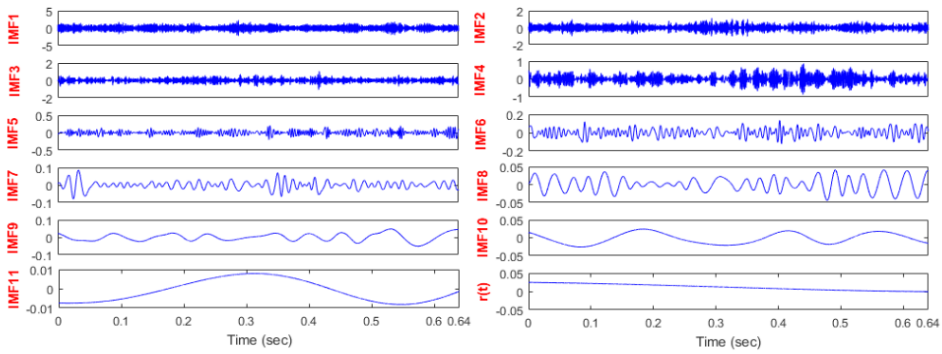


Figure 6 The signal decomposition by EMD of healthy gear

looking at the time trend plot of healthy gear and tooth crack of 20% (Fig. 4a and b, Fig. 5a and b), we pointed out that it is not possible to detect the defect of the gear, but the vibration signals corresponding to the tooth crack of 40% (Fig. 4c and 5c) characterized by periodic impulses caused by cracked tooth.

As described in Sec. 2, the kurtosis values were calculated for acceleration signals from healthy gear and tooth crack from 20% and 40% with loads of 1.5 and 3Nm, Then the EMD method was applied to decompose each signal, in Figs. 6–8 we can see the IMFs given by EMD which correspond to healthy gear and tooth crack from 20% and 40% with 1.5Nm. We have obtained 12 IMFs for each signal, the last is the residue.

After that, applying the equation (3), we have calculated the residual signal of each IMF by subtracting the residual IMFs that the kurtosis is below 3 in Tab. 3, we have obtained the residual signal (Fig. 9). Finally, we have calculated the Kurtosis values for the residual signals.

The equipment, discharged at the beginning, is then subjected to two loads with

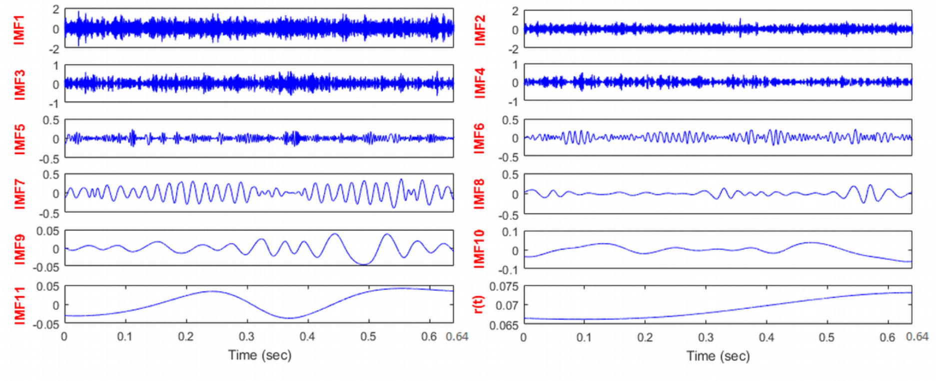


Figure 7 The signal decomposition by EMD of gear with tooth crack from 20%

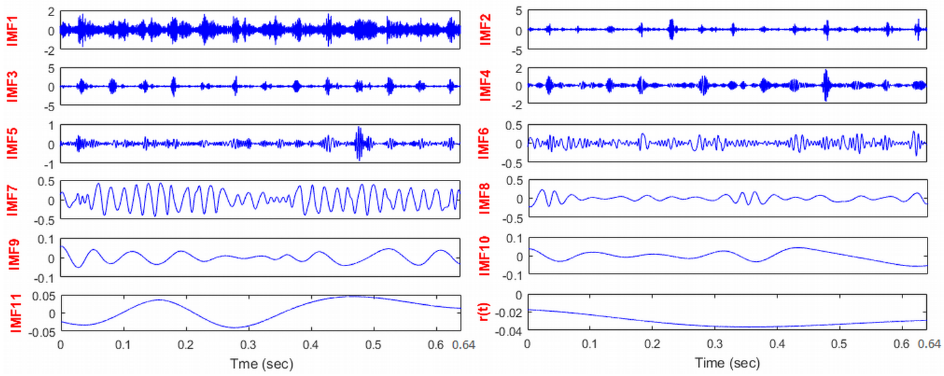


Figure 8 The signal decomposition by EMD of gear with tooth crack from 40%

Table 3 Kurtosis values for the residual IMFs of the faulty gears

	1.5 Nm of load		3 Nm of load	
	20% crack	40% crack	20% crack	40% crack
IMF1	**3.3195**	**3.5355**	**3.2943**	**13.4498**
IMF2	**3.7001**	**3.9010**	**4.0345**	**18.0193**
IMF3	**3.0568**	**4.5482**	**3.0206**	**9.4445**
IMF4	2.9370	**3.4969**	2.9697	**8.6551**
IMF5	**3.2419**	2.8644	**3.2907**	**9.7418**
IMF6	2.7822	**3.2552**	2.6774	**3.5232**
IMF7	2.5642	2.5402	**3.1165**	**3.8947**
IMF8	2.8369	2.3126	2.5641	**3.1142**
IMF9	2.0430	2.1144	2.9764	2.7912
IMF10	2.3801	1.9902	2.0031	2.6132
IMF11	1.8690	1.9236	1.9509	2.2236
IMF12	1.7355	1.8475	1.7604	2.3698

a regular difference. These are provided by a brake mounted on the driven shaft. Figures 10 and 11, show that the kurtosis values do not vary significantly for raw signal defects by 20%, because the pulses due to the appearance of the defects are

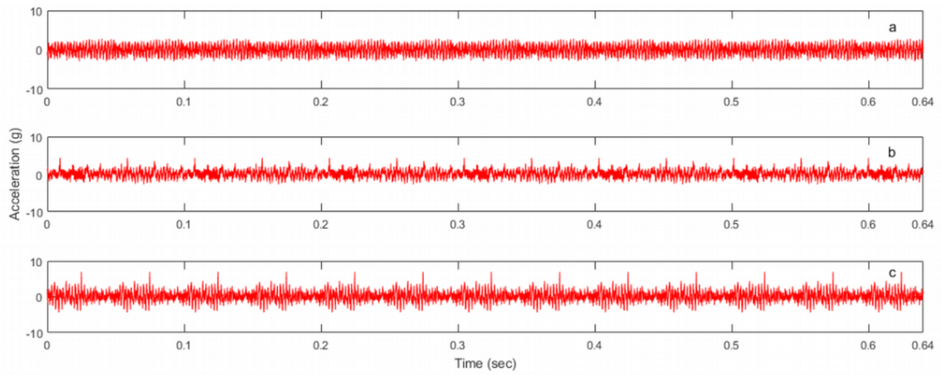


Figure 9 Residual signal of gear for 1.5Nm of load: (a) healthy gear (b) and (c) tooth crack from 20% and 40%

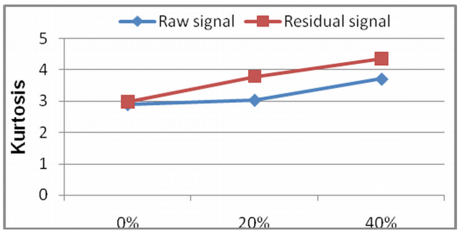


Figure 10 Kurtosis values variation of vibration signal with torques of 1.5Nm

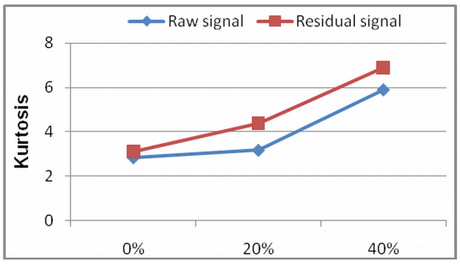


Figure 11 Kurtosis values variation of vibration signal with torques of 3Nm

masked by noise, but when we apply the combined method of EMD And residual signal, we can clearly see the crack defect with 20%, so the method can be used to identify early cracks in the gearboxes.

5. Conclusions

The results presented in this study demonstrate that the combination method of EMD and residual signal can be used to identify early crack damage in gear boxes. The temporal indicator kurtosis of residual signal is used to detect a crack in gears in different configurations using the EMD method. An experimental study of crack defects with light loads on spur gear teeth of cylindrical gears has been initiated.

The results obtained are interesting and have made it possible to understand the evolution of the sensitivity of the residual signal based on EMD method. The empirical mode decomposition technique (EMD) has been used to extract the related defects' characteristics of the vibration signals acquired from the transfer box. The results show the advantage of the combined method EMD and RS technique for an effective evaluation of tooth cracking in spur gears.

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