Extraction of Hu-Descriptors from Short-Term-Fourier Transforms in Non-Stationary Gear Fault Diagnosis

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Abstract: In industries, all the machines have different types of mechanism for its stable operation. Among that the most important mechanism for transmitting power and to regulate speed is the gears. Continuous monitoring of such gears is needed because of its high precision and high speed of operation conditions. The teeth of the gear get distorted because of ageing and varying load conditions which leads to non-stationary operation conditions. This paper is attempt to analyze the effectiveness of modern time-frequency distributions called the Short-Term Fourier Transform (STFT). Also, the new non-linear features called HU descriptors are extracted from the Short-Term Fourier Transform (STFT) to increase the effectiveness of non-stationary fault diagnosis in spur gears.

Keywords: Gear fault, Short Term Fourier Transform (STFT), HU descriptors, Time-Frequency distributions.

Introduction

Gears are one of the essential systems for power transmission. In gears there are many possibilities of failure are there, which may lead to shut down of the entire system. Thus continuous monitoring of gears is necessary to decrease the possibility of mechanical failure. Faults in the gear can be identified through vibration signature. Each machine has its own vibration signature. Vibration signature of a system changes with the state of the system. Using this method, the defects may be observed before it goes to critical. In general, value type analysis is preferred for fault diagnosis[1]. This value type analysis is very useful to predict wear related damage progression in gear transmission system[2].Traditionally the time and frequency domain analysis are used for vibration signal analysis[3]. In time domain the features of faulty gears are compared with the normal gears. In frequency domain Fast Fourier Transform (FFT) is used to identify the faults. The main disadvantage of using the FFT is that it is applicable only for the stationary signal. But machine signals are usually non-stationary signal[4]. Then time frequency domains have started playing the significant role because it overcomes the fact that some part of the machine vibration signature are difficult to read due to the characteristics of vibration signature and the noise. To process the non-stationary signal, the popular Short-Term Fourier Transform (STFT) is introduced[5]. Further Zhao-Atlas-Marks transforms is also used in analyzing the time frequency domain of gear signal[6]. In this work, the new non-linear features called HU descriptors are extracted from the STFT to increase the effectiveness of non-stationary fault diagnosis in spur gears. Because in case of non-linear features a small change in input may cause a large change in output. The vibration signals of the spur gear under normal and faulty conditions such as wear tooth, worn out tooth, and worn out tooth under loading is considered for the analysis.

Application of Non-Linear Features

This paper discusses the application of non-linear features in STFT transforms for the fault diagnosis which have been explained in detail in this section:

Short Term Fourier Transform (STFT)

In the continuous-time case, the function to be transformed is multiplied by a window function which is nonzero for only a short period. The Fourier transform (a one-dimensional function) of the resulting signal is taken as the window is slide along the time axis, resulting in a two-dimensional representation of the signal. Mathematically, this is written as:
Short Time Fourier Transform = $X(\tau,\omega) = \int_{-\infty}^{\infty} x(t)w(t-)e^{-j\omega t}\,dt$

Where w(t) is the window function, commonly a Hann window or Gaussian window bell centered around zero, and x(t) is the signal to be transformed. X (τ,ω) is essentially the Fourier Transform of x(t)w(t-τ), a complex function representing the phase and magnitude of the signal over time and frequency.

HU descriptors

Hu defines seven of these shape descriptor values computed from central moments through order three that are independent to object translation, scale and orientation. Translation invariance is achieved by computing moments that are normalised with respect to the centre of gravity so that the centre of mass of the distribution is at the origin (central moments). Size invariant moments are derived from algebraic invariants but these can be shown to be the result of a simple size normalisation. From the second and third order values of the normalised central moments a set of seven invariant moments can be computed which are independent of rotation. From the normalised central moments a set of seven values can be calculated and are defined by:

$$Nh1 = \eta_{20} + \eta_{02}$$

$$Nh2 = (\eta_{20} - \eta_{02})^2 + 4\eta^2_{11}$$

$$Nh3 = (\eta_{30} - 3\eta_{12})^2 + (\eta_{03} - 3\eta_{21})^2$$

$$Nh4 = (\eta_{30} + 3\eta_{12})^2 + (\eta_{03} + 3\eta_{21})^2$$

$$Nh5 = (3\eta_{30} - 3\eta_{12})(\eta_{30} + \eta_{12})[(\eta_{30} + \eta_{12})^2 - 3(\eta_{21} + \eta_{03})^2] + (3\eta_{21} - \eta_{03})(\eta_{21} + \eta_{03}) \times [3(\eta_{30} + \eta_{12})^2 - (\eta_{21} + \eta_{03})^2]$$

$$Nh6 = (\eta_{20} - \eta_{02})^2[(\eta_{30} + \eta_{12})^2 - (\eta_{21} + \eta_{03})^2] + 4\eta_{11}(\eta_{30} + \eta_{12}) + (\eta_{21} + \eta_{03})$$

$$Nh7 = (3\eta_{21} - \eta_{03})(\eta_{30} + \eta_{12})[(\eta_{30} + \eta_{12})^2 - 3(\eta_{21} + \eta_{03})^2] + (3\eta_{12} - \eta_{30})(\eta_{21} + \eta_{03}) \times [3(\eta_{30} + \eta_{12})^2 - (\eta_{21} + \eta_{03})^2]$$

Experimental Studies

In main objective of the experimental study is to take the vibration signals for the normal gear, wear tooth, broken tooth and broken tooth under a certain load. The faults introduced in the gears, experiment setup and the procedures are discussed below.

Faults introduced

The three faults considered in this work are wear tooth, broken teeth and broken teeth under load. The faults on the gears are created by using Electric discharge machining (EDM**).** The amount of faults made is shown in table 1.

Table 1 Amount of fault

Si.no	Faults	Dimensions
1	Wear tooth	0.7 mm
2	Broken tooth	5 mm
3	Broken toothunder load	5mm under load (100N)

Experimental setup

The experimental setup is shown in fig.1. It consists of a gear box, a 3-phase induction motor and a variable frequency drive. The gear box used for this experiment is a single stage gear box. The specifications of the gears are shown in table 2. To introduce a wear on the gear, En 24 steel is used as the material without any heat treatment. The one side of the gear box is connected to the 3-phase induction motor through a coupling. A 5-hp 3-phase induction motor is used for this experiment and the maximum speed of the motor is 1500rpm. Another side of the gear box is connected to a test bearing through a coupling and the weights are added at the shaft. The variable frequency drive is used to change the speed of the motor. And SAE 30 oil is used as the lubricant in gear box without any anti wear properties.

Experimental procedure

First the accelerometers are fixed at the two bearings of the gearbox. The gearbox could run at 400rpm, the speed is controlled by the variable frequency drive. First the normal gear is fixed and the vibration signals from the left and right bearings are taken. A 4-channel Data acquisition module NI 9233 and Dewesoft (version 7.0.2) software is used to take the readings. Then the wear tooth gear is fixed and the readings are taken. Similarly, for the broken teeth and a load of 100N is introduced at the end of the shaft and the readings are taken. The sample length is set as 2014samples/second for all gears. Many trials have been done and the readings are stored in the computer memory for further analysis.

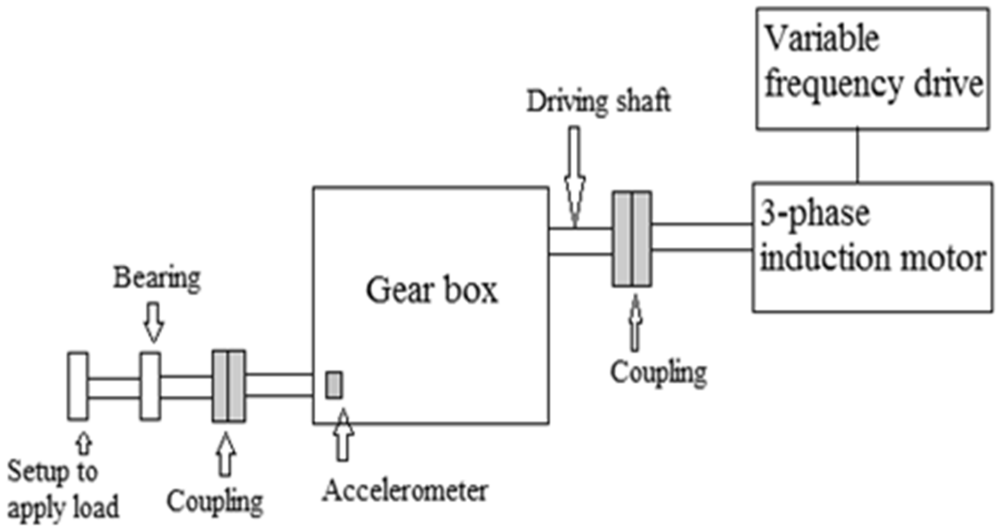

Fig.1. Experimental setup

Table 2 Specifications of Gear

Si.No	Specifications	Pinion	Wheel
1.	Centre Distance	150 mm	150 mm
2.	Pitch Diameter	100 mm	200 mm
3.	Module	5 mm	
4.	Number of Teeth	20	40
5.	Face Width	25 mm	25 mm

Results and discussions

Accelerometer is used to collect the signals of defect less gear, wear tooth, broken tooth, and broken tooth under load through the experimental setup discussed in the section 2. The signals are analysed with the help of MATLAB version R2011b through time frequency toolbox for STFT and invmoments toolbox for HU descriptors. The vibration signals are shown in the fig 2 to fig 5.

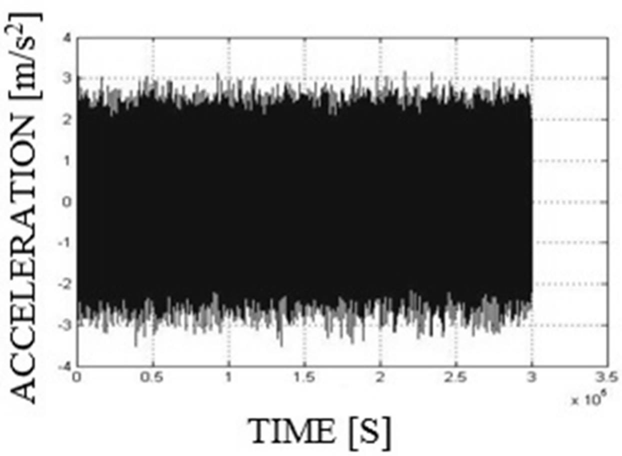

Fig. 2. Normal tooth

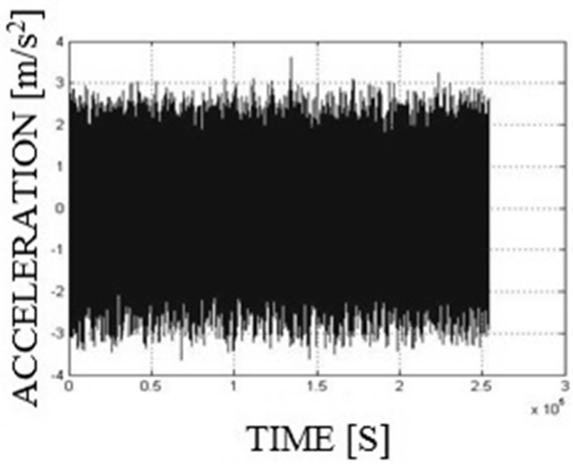

Fig. 3. Wear tooth

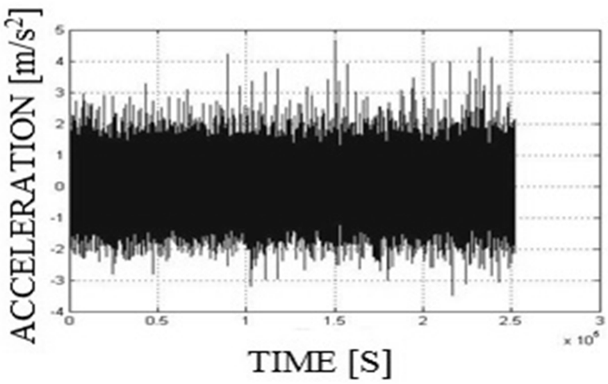

Fig. 4. Broken tooth

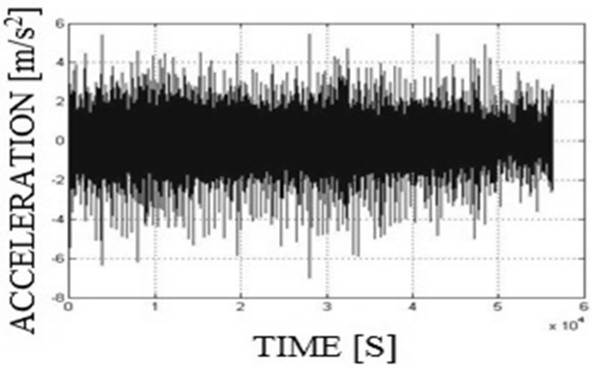

Fig. 5. Broken tooth under load

STFT

The time frequency (STFT) response of the acceleration signals taken from the normal gear, wear tooth, broken tooth and broken tooth under load are shown in fig 6 to fig 9.

The magnitude of fault frequency of gear is calculated by multiplying the rotational frequency with the number of gear. Here the number of gear teeth is 20 and the rotational frequency is 6.67Hz. Thus, the fault frequency for this gear is 133.4Hz or 0.13Hz. In STFT, the maximum energy density of wear tooth and broken tooth under load is higher than the fault frequency. From this the faults are identified in the wear tooth and broken tooth under load cases. But in the case of broken teeth, the maximum energy density is slightly less than the fault frequency. So, to increase the effectiveness and to avoid the visual errors, HU descriptors are used for analysis.

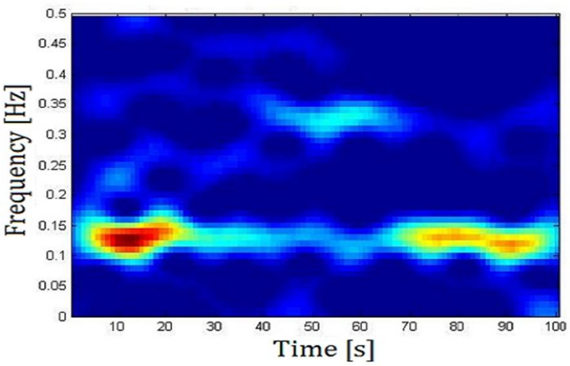

Fig. 6. Normal tooth

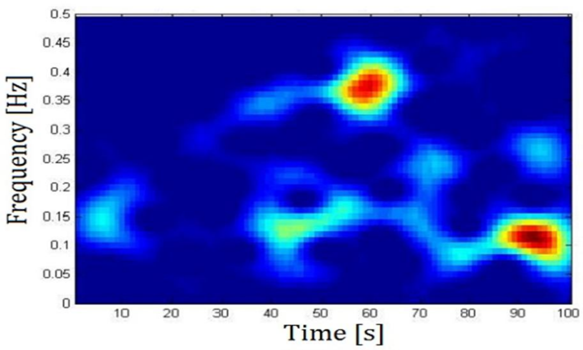

Fig. 7. Wear tooth

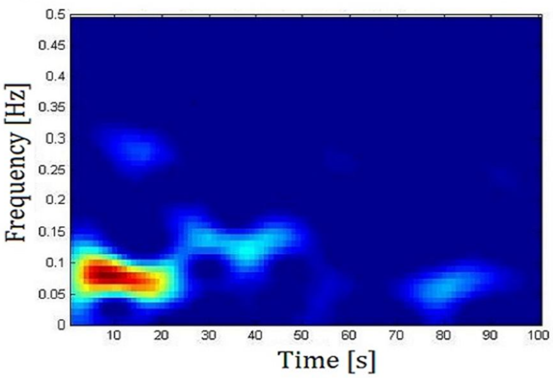

Fig. 8 Broken tooth

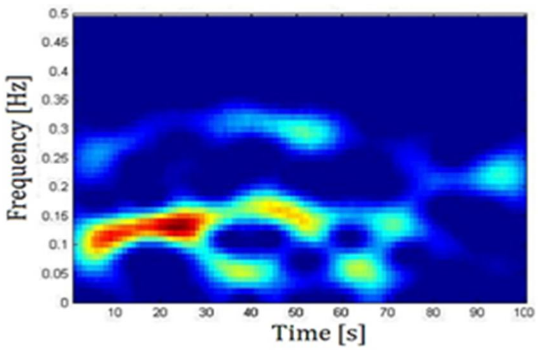

Fig. 9 Broken tooth under load

HU descriptor

The non-linear time frequency domain features (HU descriptor) are evaluated and noted in table 3 for all the cases.

Table:3 Non-linear time frequency domain features (HU descriptor)

Hu	Normal Tooth	Wear Tooth	Broken Tooth	Broken tooth under load
Nh1	0.002055187	0.002149584	0.002448933	0.002027383
Nh2	3.99e-07	3.81e-07	3.77e-07	3.26E-07
Nh3	6.99e-13	5.83e-12	8.69e-12	4.42E-12
Nh4	7.77e-12	2.60e-11	2.79e-11	2.90E-11
Nh5	1.31e-23	1.42e-22	-8.29e-23	-2.59E-22
Nh6	-4.60e-15	1.50e-14	1.03e-14	-8.63E-15

In the above features, the values of the descriptors NH3, NH4 and NH6 for the faulty gears, are higher than the normal gears. And the remaining descriptor values are non-uniformly varying. So, the values NH3, NH4, NH6 can be taken into account to identify the faulty gear. In normal gear, NH3 value is 6.99E-13, NH4 value is 7.77E-12 and NH6 value is 1.25E-23. These values are considered as reference for the fault diagnosis.

Conclusion

This paper has presented the use of non-linear features in non-stationary signal analysis, particularly in STFT distributions, toward gear fault deduction. The non-linear features are evaluated for both the normal and faulty gears and compared to identify the fault. In which NH3, NH4 and NH6 values of the faulty gears are higher than the normal gear. Thus, these three features are used for the identification of fault. The HU descriptors offered a superior performance with high accuracy which is demonstrated with the results in section 4.2 in detail. So, to increase the effectiveness of STFT transform in non-stationary gear fault diagnosis, the non-linear features are evaluated to identify the faults.

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