Worm and wheel gears fault frequency extraction using minimum entropy deconvolution based envelope of the vibration signal

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Abstract. Identification of fault frequency or hunting tooth frequency of the gears is a challenging task especially in worm and wheel gears which operate at relatively slow speed. The impulses due to fault in meshing gears are not strong enough to expose themselves in the signal acquired from the gearbox. Fault features remained buried beneath noise from other components of the gearbox and surrounding. A scheme of signal processing has been proposed to deconvolute the signal and enhance the impulses in the signal obtained from meshing faulty teeth. Further, in this scheme, the envelope of the signal extracts the period of faulty tooth meshing which is verified from theoretical results and found in good agreement.

1. Introduction:
The combination of worm and wheel allows high reduction in rotational speed and enhances the torque transmission. This set of gears has wide applications in devices both at domestic level and in industrial machinery like agitators, conveyors, crushers, cranes, elevators, feeders, small ball mills, mixers, cooling towers, extruders, packaging, filters etc. In order to avoid breakdown due to failure of gearbox, an efficient monitoring system is required to detect faulty components in it (gearbox). Many condition monitoring techniques are developed by various researchers and are available in the literature. On-line wear debris analysis techniques have been implemented by Feng et al. [1] on gears in order to detect the condition of the gears. Jena et al. [2-3] have explored vibration signal and acoustic emission analysis to identify the angular positions of two defective teeth. They extracted the presence of fault in spur gear using statistical features and also identified location of multi defects in a gear using analytic wavelet transform (AWT) with time marginal integration (TMI). Venker et al. [4] have utilized conventional spectrum and continuous wavelet transform to detect the fault in the gears of automobile gear box. Singh and Zhao [5] proposed a signal processing scheme based on empirical mode decomposition (EMD), envelope and pseudo-fault signal for separating fault features of different rotating components in the machines. Dhamande et al. [6] investigated the defects in gear and bearing using statistical approach such as root mean square (RMS) of healthy and faulty components, along with standard deviation, kurtosis, crest factor etc. and artificial neural networks (ANN). They concluded that the presence of defects whether in gear or bearing or in combination leads to increase in overall vibration relative to healthy condition of gear box. Li et al. [7-8] have proposed autocorrelation local cepstrum to identify the weak fault features. Kumar and Kumar [9] proposed a undecimated and adaptive wavelet transform to enhance the weak fault features in the signal of faulty bearing to quantify the size of the defect in bearing. Undecimated and adaptive wavelet transform denoised the signal effectively and produced high coefficient for the low-frequency components in the signal. Shao et al. [10] presented an approach for calculating root mean square (RMS) using angle domain signal within small angular range and order tracking spectrum. Angular domain synchronous average (ADSA) reduces noise level and enhances signal to noise ratio, which extract the information related to fault of helical gears at slow speed. The methods developed so far does not give satisfactory results while dealing with signal from worm and
wheel giving a very low speed as output. Hence there is a need to develop a suitable processing scheme to handle signal from high reduction gears such as worm and wheel.

Present paper proposes a signal processing scheme to extract the fault features in worm and wheel gearbox. The scheme deconvolutes the signal for taking envelope of the same. The scheme is capable of removing the noise, deterministic pattern of gears and enhances the impulsiveness in the residual signal. Further it exposes the periodic impulses to ensure the health condition of the gears.

2. AR_Minimum entropy deconvolution:
Autoregression (AR) filter segregates the deterministic pattern from the gear mesh signal. It gives the output as residual: which is difference of the original signal and AR predicted deterministic pattern. But the AR filter does not recognize the abrupt impulses aroused due to localized tooth fault in gear. To improve the effectiveness of the filter, autoregression (AR) and minimum entropy deconvolution (MED) are combined [11]. The output of AR is used as input of MED filter which optimizes the set of coefficients of the filter that gives the signal having highest value of kurtosis. High value of kurtosis reflects impulsiveness in the signal. Sequence of application of MED on AR filter and its effect is illustrated in figure 1.

![Figure 1: Process of enhancing fault impulse using AR-MED filter.](image)

3. Envelope detection
During the interaction of the faulty tooth with other gear, an impulse is generated. Since this impulse is for a very short duration in comparison to the time interval for the next impulse from the same faulty tooth, the energy gets distributed over the wider range of frequencies starting from a very low level. Conventional techniques find it difficult to extract gear tooth fault due to broad distribution of energy from impact. Amplitude demodulation using envelope detection extracts repeated impulses. The envelope or instantaneous amplitude is modulus of analytic signal. Analytic signal is formed by the combination of real and imaginary part, whose real part is the original signal $x(t)$ and imaginary part is Hilbert transform of original signal $H[x(t)]$. Analytic signal with Hilbert transform is given by equation 1.

$$y(t) = x(t) + iH[x(t)] = Y(t)e^{\beta(t)}$$  

where $Y(t) = \sqrt{[x(t)]^2 + [H[x(t)]]^2}$ and $\beta(t) = \tan^{-1}\left(\frac{H[x(t)]}{x(t)}\right)$

$Y(t)$ is the envelope of $y(t)$.

For original signal $x(t)$, its Hilbert transform $H[x(t)]$ is a convolution of original signal and $\left(\frac{1}{\pi t}\right)$ time function. The Hilbert transform is given in equation 2 [12].

$$H[x(t)] = \frac{1}{\pi t} * x(t)$$  

where, $t$ is time parameter. In actual practice the signal acquired from the machine is amplitude modulated, therefore demodulation is required to extract the fault related information.
4. Proposed feature extraction scheme:

![Flow chart of proposed scheme](image)

Raw signal acquired from test rig is down sampled in order to reduce the processing time. Down sampled signal is further filtered using AR_MED filter. AR filter eliminates the deterministic pattern of gear mesh in the signal and MED enhances the impulsiveness in the signal. Since the MED is based on the appropriate set of coefficients, it maximizes the kurtosis value of the signal. High value of kurtosis represents the impulsiveness in signal irrespective of periodic or aperiodic impulses. In order to extract the periodic impulses, envelope of the signal is utilized. Further envelope of the signal is analysed to extract the fault features. Hunting tooth frequency (HTF) is obtained by equation 3.

\[
HTF = \frac{1}{\text{period of repetition of faulty tooth in meshing}}
\]  

The gear meshing frequency (GMF) is obtained by equation 4.

\[
\text{Gear meshing frequency}(f_{GM}) = HTF \times \text{Gear ratio}
\]

5. Experimentation and data acquisition:

Experiments are carried on single stage worm and wheel gearbox having gear ratio 20:1. Number of teeth on wheel are 20. The wheel has pitch circle diameter of 65mm. The worm is driven by a 50 Hz DC motor (WAFRO) of rating 1hp operating at 2880 rpm connected through a flexible coupling. An image of test rig is shown in Figure 3.

![Test Rig](image)

Vibration signals have been acquired using internal excitation based piezoelectric uniaxial PCB accelerometer of 100 mV/g sensitivity placed over the bearing seat of the wheel shaft. A seeded missing tooth faults has been introduced on wheel tooth as shown in Figure 4. Three sets of data have been acquired at speeds 980 rpm, 1575 rpm and 2370 rpm each for healthy as well as faulty gear conditions at sampling rate 70 kHz. Since the hunting tooth frequency of worm wheel is relatively low, signal for longer duration is required to process it for extraction of HTF. Keeping it in view signal of 5 seconds duration has been processed for each condition.
6. Results and Discussion:
Data acquired from test rig is processed to extract the fault features. The raw signal of 5 seconds duration each at speeds 980 rpm, 1575 rpm and 2370 rpm under healthy condition have been shown in Figure 5(a-c) and its spectrum is shown in Figure 5(d-f) respectively. Gear meshing frequency (GMF) is depicted in the spectrum of signal. GMFs are 16.25 Hz, 26.23 Hz and 39.5 Hz have been observed for speeds: 980 rpm, 1575 rpm and 2370 rpm respectively. But there are no evidences of fault frequency or hunting tooth frequency (HTF). In order to extract the hunting tooth frequency (HTF), signal is further processed using proposed scheme and shown in Figure 6(a-f). As no such repeating impulses are observed, it indicates healthy condition of the gear.

![Image](image_url)

Figure 5: Raw signals and their spectrum under healthy condition: (a) Signal at 980 rpm (b) Signal at 1575 rpm (c) Signal at 2370 rpm (d) Spectrum of signal at 980 rpm (e) Spectrum of signal at 1575 rpm (f) Spectrum of signal at 2370 rpm.
Figure 6: Signals obtained from AR_MED and their envelopes under healthy condition: (a) at 980 rpm (b) at 1575 rpm (c) at 2370 rpm (d) envelope of signal at 980 rpm (e) envelope of signal at 1575 rpm (f) envelope of signal at 2370 rpm.

In the similar way signals acquired at speeds 980 rpm, 1575 rpm and 2370 rpm under faulty condition have been processed and analysed. Spectrum of the raw signal shows the gear meshing frequencies but is unable to extract hunting tooth frequency. The raw signal and its spectrum at different speed of rotation are shown in Figure 7(a-f). In order to detect the HTFs the signals are processed by proposed scheme and it has been observed that the processed signal is able to provide the evidences of HTFs. Signal at different stages of processing for different rpm is shown in Figure 8 (a-f). High repetitive impulses are observed in the envelopes which indicates meshing of faulty tooth with worm. The periods of repetition of impulses are 1.2282 seconds, 0.762 seconds and 0.505 seconds corresponding to speeds 980 rpm, 1575 rpm and 2370 rpm respectively as shown in Figure 8 (d-f). HTFs are obtained as 0.8141 Hz, 1.3123 Hz and 1.98 Hz, for time periods 1.2282 seconds, 0.762 seconds and 0.505 seconds corresponding to speeds 980 rpm, 1575 rpm and 2370 rpm as observed from Figure 8(d-f). HTFs are verified using equation 4. It has been observed that HTFs extracted by proposed scheme is in good agreement with values obtained from equation 4.
Figure 7: Raw signals and their spectrum under faulty condition (a) Signal at 980 rpm (b) Signal at 1575 rpm (c) Signal at 2370 rpm (d) Spectrum of signal at 980 rpm (e) Spectrum of signal at 1575 rpm (f) Spectrum of signal at 2370 rpm.
7. Conclusion:
Vibration signals of the worm gearbox have been analysed using conventional spectrum and after implementing proposed scheme. Following are the conclusions:

- Conventional spectrum is only able to show gear meshing frequency (GMF) but is unable to identify the health condition of the worm and wheel gear. Proposed signal processing scheme using minimum entropy deconvolution and envelope of signal effectively extracts the hunting tooth frequency (HTF) which is an identifier of faulty gear condition.
- The present scheme of signal processing is capable to extract the weak fault features even at slow speeds of output of the order of 1 Hz.

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