DIAGNOSIS OF GEARBOX FAULTS IN AGRICULTURAL MACHINERY USING ENERGY OF TRANSIENT FEATURES

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Abstract
Gear mechanisms are widely used in agricultural and other kind of machinery. For this reason, gear health monitoring has been the subject of intensive investigation and research. Among several other methods, vibration measurement and analysis is considered as a practical means for fault detection in gearboxes. In this work, a hypothesis is made that local faults appear as transient signals in the vibration time-series. The energy content of these transient features increases as the magnitude of damage increases. Data were collected from an experimental rig that consists of two electrical machines, a pair of spur gears, a power supply unit and the necessary speed control electronics. The vibration signal generated by the gearbox was picked up by an accelerometer bolted to the pinion body and the electrical signal was transferred to an external charge amplifier through slip rings and recorded by a PCMCIA acquisition card. The time-series was then analyzed with the newly proposed Empirical Mode Decomposition scheme [1], in which the signal is decomposed to a group of oscillatory functions called the intrinsic mode functions. The instantaneous energy is shown to obtain high values when defected teeth are engaged and therefore it can be directly related to damage magnitude. By using the results of these experiments, an online diagnostic system could be built resulting in improved reliability and reduced maintenance cost.

Introduction

Gear mechanisms are an important element in a variety of mechanical systems. For this reason, early fault detection in gears has been the subject of intensive investigation and many methods based on vibration signal analysis have been developed. Conventional methods include kurtosis, power spectrum and cepstrum estimation and envelope detection, which have proved to be effective in fault diagnosis and are now well established [1], [2], [3]. Their main drawback, however, is that they are based on the assumption of stationarity and linearity of the vibration time-series under study.

To deal with non-stationary signals, new techniques such as time-frequency distributions and wavelets have received attention and gained acceptance [4], [5], [6]. The wavelet transform is by far the most popular technique. The time and frequency resolution however is a compromise, as a large scale wavelet is chosen for determining general signal features and a small scale wavelet for extracting the signal details. Consequently, time localization is poor for low frequency signals and frequency resolution is poor for high frequency signals. Another shortcoming of the wavelet method is the fact that the analysis depends on the choice of the wavelet function and only signal features that correlate well with the shape of the wavelet function have a chance to lead to coefficients of high value.

In the quest of accurate time and frequency localization Huang et al. [7] proposed the Empirical Mode Decomposition (EMD) scheme which offers a different approach in time-series processing. In this work, the EMD algorithm is used for detectikn and prediction of gear faults. A hypothesis is made that local faults appear as transient signals in the vibration time-series. Their energy content increases as the magnitude of damage increases. A detection and prediction is presented that is based on the energy content of transient features.

Empirical mode decomposition

The EMD method decomposes a time-series into a finite set of oscillatory functions called the intrinsic mode functions (IMF). An IMF is a function that satisfies two conditions: (1) the number of extrema and the number of zero crossings must either equal or differ at most by one; (2) the running mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. The procedure to decompose a signal into intrinsic mode functions is as follows. First, the local extrema of the signal $x(t)$ are identified. The local maxima are connected together forming the upper envelope $u(t)$ and the local minima are connected forming the lower envelope $l(t)$. This connection is implemented by a cubic spline interpolation scheme. The running mean is defined as

$$m_1(t) = \frac{l(t) + u(t)}{2} \tag{1}$$

Then $m_1(t)$ is subtracted from the signal $x(t)$, resulting in the first component $h_1(t)$, i.e.:

$$h_1(t) = x(t) - m_1(t) \tag{2}$$

The component $h_1(t)$ is now examined if it satisfies the conditions to be an IMF. If not, a process named by Huang as the *sifting process* should be followed until $h_1(t)$ becomes an IMF. In the sifting process $h_1(t)$ is treated as the new data. The first IMF $C_1(t)$ is subsequently subtracted from the original signal $x(t)$, the difference called the first residue $r_1(t)$.

$$r_1(t) = x(t) - C_1(t) \tag{3}$$

The residue $r_1(t)$ is taken as the new signal and the sifting process is applied from the beginning. As a result, the signal $x(t)$ will be decomposed into a finite number of IMFs $C_j(t)$. The sifting process ends when the last residue $r_N(t)$ is a constant or a monotonic function.

Experimental set-up

The experimental rig consists of two electrical machines, a pair of spur gears, a power supply unit with the necessary speed control electronics and the data acquisition system. Referring to figure 1, a DC machine of 1.5 kW rotates the pinion. The load is provided by an AC asynchronous machine, which is configured as a brake. The transmission ratio is 35/19 = 1.842, which means that an increase in rotational speed is achieved. The vibration signal generated by the gearbox was picked up by an accelerometer bolted to the pinion body and the electrical signal was transferred to an external charge amplifier through slip rings. The sampling interval was Δt = 0.05 ms corresponding to a sampling frequency f_s of 20 kHz. The signal was lowpass filtered at 5 kHz through a 4^{th} order Bessel type filter. Data was stored for post processing to a portable PC. The acquisition system was flexible enough to be used in actual industrial conditions. A number of 2^{15} = 32768 samples have been acquired in all experiments corresponding to a time-history length of 1.638 s.

Fault identification procedure

In all cases the rotational speed of the pinion axis was kept relatively constant at 300 rpm (5 Hz). This resulted in a meshing frequency of 35 x 5 = 175 Hz. The load varied from 10 Nm to 18 Nm. The magnitudes of damage tested varied from a crack of 15% of tooth root up to a crack of 75% of the tooth root. The intermediate damage levels were 33% and 50%. The cases of a healthy gear and a gear with tooth loss have been also examined for completeness. For each single damage scenario 10 experimental runs were conducted and the vibration data were stored on the hard disk of a portable computer.

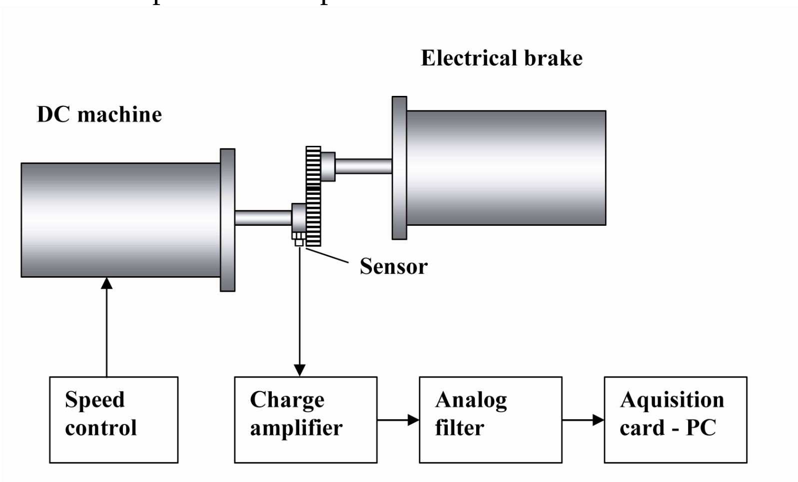

Figure 1: Experimental test rig.

The vibration time-series of a gear pair with a 15% crack (load 10 Nm) is decomposed using the EMD algorithm. The IMFs are presented in figure 2. The first row represents three periods (600 ms) of the vibration signal for time reference. From a total of nine intrinsic mode functions found, only the first four are depicted, because the energy of modes C_5 to C_9 is very low. Mode C_1 contains the highest signal frequencies, mode C_2 the next higher frequency band and so on. The transient caused by the crack is clearly captured in modes C_1 and C_2 and takes the form of periodic pulses with a period of 200 ms, which coincides with the period of shaft revolution.

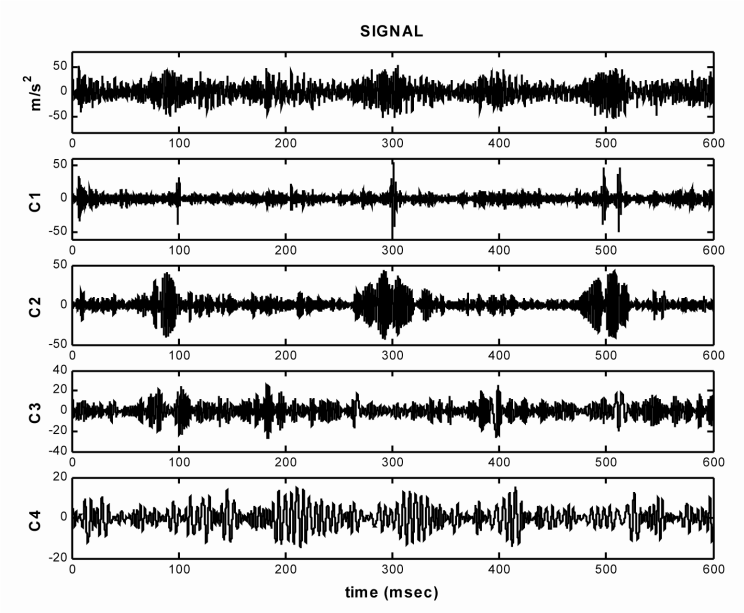

Figure 2: Decomposition of the vibration signal into intrinsic mode functions.

It seems that mode C_2 best represents the time scale of the transient caused by gear damage and for this reason it is selected as a suitable diagnostic feature for all subsequent experiments. In particular, the energy of mode C_2 will be used defined as

$$E_2(t) = \frac{1}{2} A_2^2(t) \tag{4}$$

where $A_2(t)$ is the mode envelope obtained from the Hilbert transform procedure. In figure 3 the calculated energies for the damaged gear pair with a relative crack magnitude ranging from 15% to 75% are presented. In addition, the case of a healthy pair and a pair that suffers from tooth loss have been added for completeness. The energy of mode C_2 of the healthy pair is relatively low and lacks the periodic pulses associated with crack type damage. The peak energy of a gear pair with a 75% crack is more than three times that of a pair with a 15% crack. Tooth loss as expected is easily identified, because the energy is more than ten times greater than the worst crack scenario.

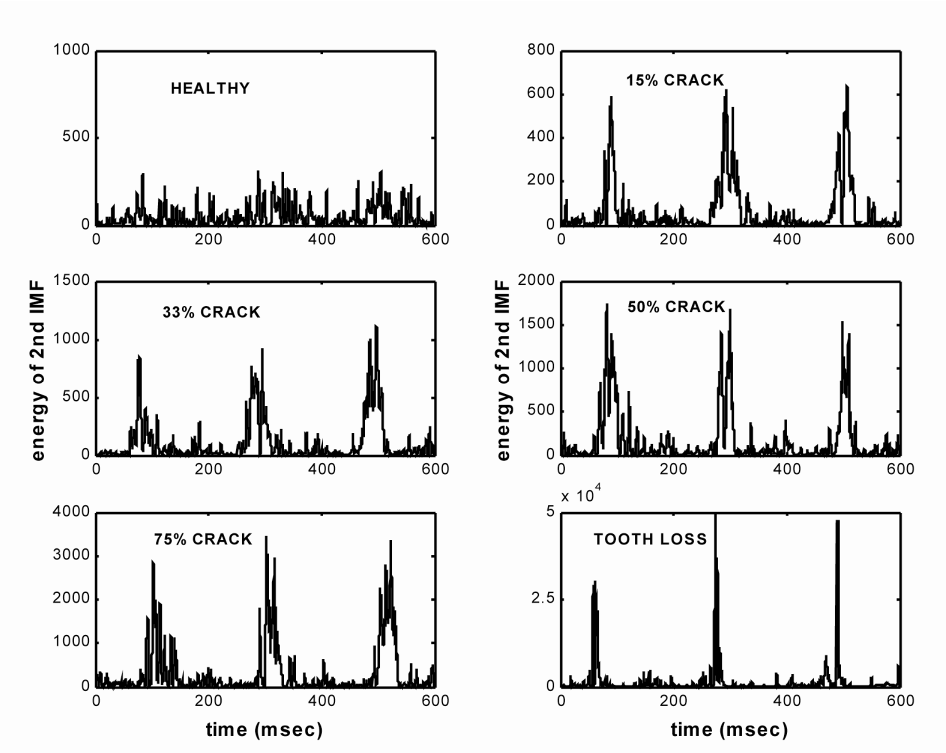

Figure 3: From top to bottm, energy of 2nd IMF for a healthy gear pair, a pair with 15%, 33%, 50%, 75% crack and tooth loss.

To derive an empirical curve that relates the energy to the crack magnitude, first the peak energy values for a certain crack size from all 10 experimental runs are recorded. This means that for a specific crack magnitude there will be 8 x 10 = 80 peak energy values available. Next, the extreme values are dropped out so that 90% of the total figures are kept. This is to make sure that the results have statistical meaning. The average value is finally computed. Figure 4 depicts the average energy versus crack magnitude.

Conclusions

In this paper, a method for gear fault identification was presented based on the newly developed Empirical Mode Decomposition algorithm. The method is not based on the *a priori* selection of a kernel function, but instead it decomposes the signal into intrinsic oscillation modes derived from the succession of extrema. It has been shown that any defect in the form of a crack or tooth loss is manifested as an increase in the envelope amplitude of one or more of the intrinsic modes. The defect evolution can be monitored by computing the energy of the intrinsic mode that is most sensitive to damage.

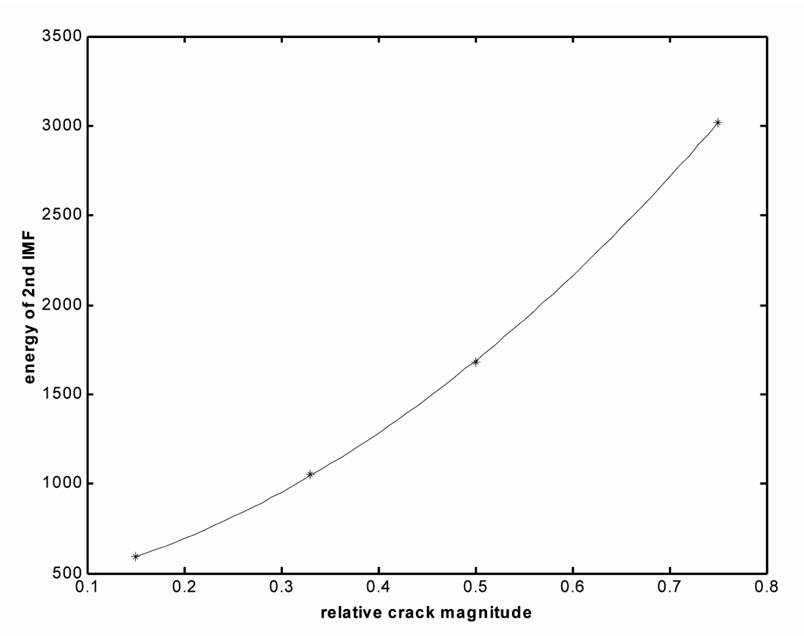

Figure 4: Energy of 2^{nd} IMF as a function of relative crack magnitude.

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