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Model Based Local Fault Detection in Helical Gears

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Abstract

In the paper the possibility of model based detection of local faults in helical gears is analysed. Presented methods allow early detection of anomalies in the time vibration signal that could be linked to the fatigue tooth damages like pitting and tooth fracture. They relies on calculation of different signal parameters for the consecutive meshes and allows for acquiring information about the disturbances of the meshing process for particular tooth pairs. They permit the observation of the energy density changes for the consecutive teeth (or tooth pairs) during the normal exploitation of the gearbox.
All the described methods are based on analysis of the time signals. Contrary to the methods based on spectral analysis these methods allow for precise localisation of gear defects and linking them to the particular pinion or gear teeth. Additionally they could be used in the procedure of gear manufacturing quality assessment.

Keywords: local meshing plane tooth fault detection, helical gear diagnostics, gear meshing model

1. Introduction

Local damage to the gear teeth causes short-term, local impulses in gear vibration signal repeated every rotation of the shaft and resulting in the phenomenon of amplitude and phase modulation [1–3]. It could be proved [4], that in the initial stage of failures development, when the energy of signal changes is particularly small, the signal is dominated by the phenomenon of phase modulation. This type of disturbances, manifested in the formation and evolution of the phenomena of amplitude, frequency, and multi-parametric modulation are referred to as low-energy [5]. Low-energy means that the power increase of the vibroacoustic signal as a result of the development of nonlinear effects is small compared to the changes in the power structure of the individual meshing harmonic.

The main difficulty with studying these phenomena stems from the fact that in the signal spectrum the difference between the frequency and amplitude modulation, particularly in the initial period characterized by a small modulation index, are difficult to distinguish. The main differences are apparent in the phase dependencies of the frequencies modulating the carrier frequency [6]. Phase relationships between these spectrum components are at the same disturbed by the difficult to be determined signal transfer function from the signal source to the sensor.

In recent years, the time-frequency and wavelet methods are used more frequently for the diagnosis of fatigue damage of gears [7-11]. These methods allow locating of the disturbed portion of the signal that could be linked to the fatigue local damages like pitting and tooth fracture. One of them is the method of spectral Kurtosis developed by Antoni [12,13]. This method allows finding the local nonstationarities occurring in the signal and determining the signal frequency for which the nonstationarity occur.

The method was adapted by Gelman [14] to detect pitting in its early stage. An example of its use in the diagnosis of tooth break in the planetary gear of a wind turbine can be found in [15].

As could be seen from the above short preview of the diagnostic methods of gears, current trends in their development are aimed at searching for the detection of individual defects. More and more methods are focused not only on the assessment of the technical state of a gear, but also on precise determining the location, type and size of the damage.

The main imperfection of most of these methods is that in the search for diagnostic information they use integration methods that are by default averaging analyzed signals. In this way, small changes in the signals appropriate for the initial phases of development failures are further minimized by the use of signal analysis algorithms.

The aim of this study was to present diagnostic methods enabling the identification of local damage of gears, allowing at the same time precise locations of the damage. The objective of these methods was the direct use of time signal processing algorithms. Their advantage is the simplicity and speed of action that is of great significance for the implementation in the autonomous transmission diagnostic systems and diagnostic systems working online. These methods were first tested on a simulation model of the gear assembly and later tested during the experiments on a back-to-back test stand.

2. Simulation model used for testing of the methods

Possibility of testing new diagnostic methods on a well identified simulation model that behaves similarly to the mechanical system simplifies their development allowing generation of signal frequently impossible to obtain in real experiments. Additionally it opens the unique chance to analyse the signal in connection with the known gear behaviour.

All the developed diagnostic methods were tested on a simulation model which uses the method of apparent interference for modelling tooth mesh [16, 17]. The simplified diagram of the model is presented on Figure 1. In the model the mating of teeth is realized by means of a complex flexible element representing meshing. It is assumed that both the gear and the pinion have the possibility of making an additional rotation in relation to the motion resulting from the revolution of their base circles. Thus the principle of the constant transmission ratio is not maintained enabling analysis of the modulation effects which occur during the toothed gear's operation. This requires modelling of the forces working between the mating teeth to define the relationship between the angular velocities of both toothed wheels. The result of such a wheels motion is the apparent interference, i.e. mutual penetration of meshing teeth which should be interpreted as their deflection. This interference can be determined by taking into account the meshing geometry and is being compensated by the flexible deformation of teeth.

While calculating the interference of the teeth and the meshing force, a series of factors which influence the geometry of meshing were taken into account:

- variable distance between gear axes (shaft runout or flexible shaft deformation),
- instantaneous error of standard contact angle,
- pitch errors, variable meshing stiffness along the path of contact etc.

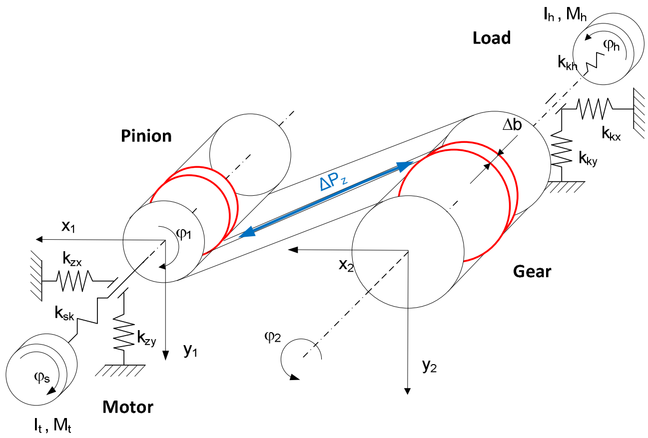

Figure 1. Simplified scheme of the simulation model of helical gear [18]

The meshing stiffness and the changes of its value for the entire path of contact were defined by way of a three-dimensional model of a toothed wheel developed with the use of FEM. More information about the model with comparison of the digital results with results obtained on the test stand could be found in [17].

3. Simulation of local gear faults

Possibility of modelling of the teeth stiffness along the path of contact makes possible simulation of tooth fatigue cracks as changes of stiffness for the particular tooth pair and pitting as a lack of contact on a part of the tooth profile. As for now the model does not allow for the similar changes of friction coefficient that would made pitting simulation more realistic.

In order to show the possibilities offered by the analysis of the signals recorded on the test bench supported with simulation model, gear acceleration measurement signals are listed together with the simulated meshing force waveforms (continuous and dashed lines on upper diagrams of Figure 2). For easiest comparison all the signals were re-scaled to obtain the same maximum amplitudes. In addition, these waveforms were compared with waveforms of the simulated meshing stiffness (bottom diagram). Presented signal fragments waveforms correspond to about half rotation of the pinion shaft.

Figure 2 corresponds to the 68 minutes of the tooth fatigue experiment [17], lasting a total of about 72 minutes, when the local signal amplitude change caused by the change of the pinion tooth stiffness caused by emerging crack at its base is evident. The corresponding simulated signal of the total meshing force that matched this was obtained for a case of reducing the stiffness of one of the teeth of the pinion by about 6%. It is worth noting that despite of various manufacturing and mounting deviations of the transmission, the amplitude of the signal transmissions in the damaged spot does not still exceed the peak amplitude of the entire signal.

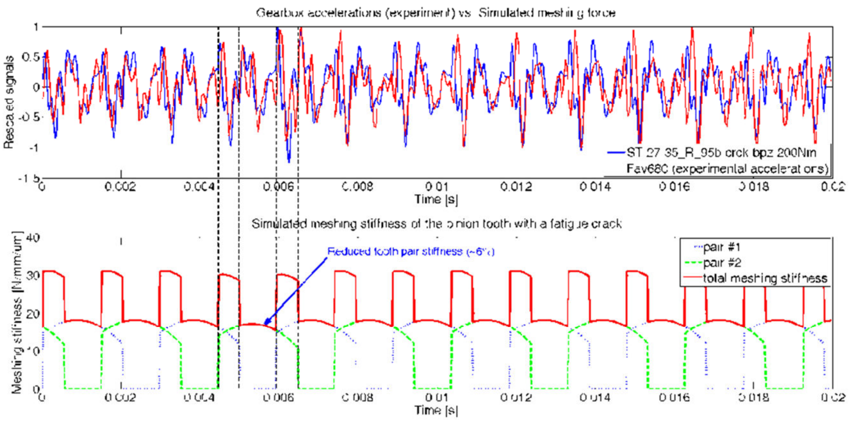

Figure 2. Comparison of gearbox acceleration recorded during the experiment and simulated meshing force for 6% reduction of stiffness on one tooth pair

On the diagrams on Figure 2, using simulated stiffness waveforms, the vertical cursors were used to mark the changes in mesh conditions. Successively: entering of the damaged tooth into two-pair contact, beginning of the one-pair contact, second beginning of the two-pair contact and exiting from the contact of the damaged tooth. It should be noted similarity of the total meshing force waveforms obtained through simulation (with a fatigue crack at the base of the tooth) to the actual measurement results of the gear. Please note that the pitch errors in the simulation were chosen at random, not mapping actual deviations of the test drive. Additionally, used a model is not completely consistent with a kinematics of the back-to-back test stand.

Closer look at Figure 2 point out slightly increased amplitude and disturbed time waveform during the second two-pair contact phase of the pair with a damaged tooth. Detailed analysis of these waveforms allows drawing conclusions according to the quality of meshing in case of emerging tooth crack. Entering into contact of the damaged tooth causes only slight disturbances in the signal. This is due to its higher stiffness during the contact around the tooth base and the fact that the contact is two-pair. Working properly previous pair of teeth then carries most of the load torque and reduce of the stiffness of the damaged pair is of minor importance.

Significant changes in the signal occur at the time of the transition to one-pair contact, since the occurrence of increased susceptibility of the tooth gap caused by fatigue causes the increased deflection, resulting in a greater impulse of force at the time of entering into contact of the next pair of teeth [19]. Additional impulse is visible in the moment of exiting from the contact of the damaged pair.

4. Methods of detection of local disturbances in the gear signal

Local disturbances of the vibroacoustic signal caused by fatigue defects discussed in the previous chapter could be detected with the use of envelope analysis. Signal envelope is usually calculated as the absolute value of the analytic signal [20-22].

$$A(t) = |\tilde{x}(t)| = \sqrt{x^2(t) + \mathcal{H}[x(t)]^2} \tag{1}$$

As calculating Hilbert Transform is time and resource consuming in the digital systems requiring performing FFT and inverse FFT alternatively Teager Kaiser Operator (TKEO) could be used to obtain similar results. TKEO energy operator was first proposed by Teager [23], but the method of its calculation for digital signals and analyzes its properties for the first time gave Kaiser [24].

TKEO operator is the operator of a non-linear, for continuous signals it has the following form:

$$\Psi[x(t)] \triangleq \dot{x}^2(t) - x(t)\ddot{x}(t) \tag{2}$$

This operator allows the estimation of the instantaneous signal energy, so-called. Teager energy, and is often used in the process of demodulating signals instead of the traditional approach of using a Hilbert transform [25-26].

For digitally sampled signals Teager Kaiser Energy Operator takes the form:

$$\Psi[x_n] = x_n^2 - x_{n-1}x_{n+1} \tag{3}$$

where $x_{n-1,} x_n , x_{n+1}$ are consecutive signal samples.

Let us note the simplicity of calculation resulting in multiplying the signal by itself and multiplication of the signal by the time shifted signal, which is very easy to obtain in digital systems. Trouble-free is also its online calculation since it requires simultaneous access to only the last three samples of the signal. Note also the similarity of the operator (3) to the square of the amplitude of the signal (see also Figure 3).

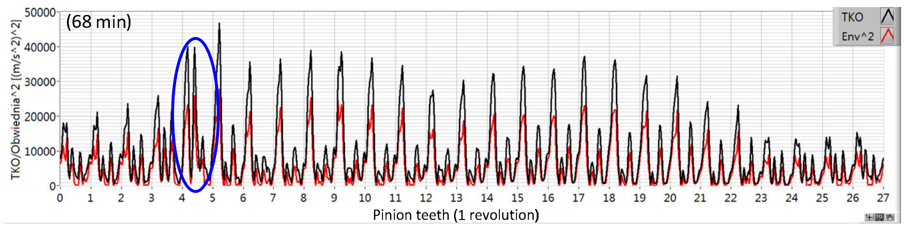

Figure 3. Comparison of squared envelope and TKEO for the acceleration signal from the 68 min. of the experiment (see Figure 2)

As it was proved above pure signal envelope is not sensitive to the detection early stages of defect resulting in subtle changes of the structure of time signals. In the work [27] author proposes a methodology to diagnose such lesions based on the segmentation of instantaneous signal power. It was later developed in the works [28-29].

The method involves comparing each of successive segments of the envelope of the averaged signal synchronously related to the lengths of the transverse radial pitch. A contractual beginning of segments are determined by the geometry of the gears and shaft speed marker, and therefore shifts of the beginning of contacts resulting from teeth inaccuracies, def lection of teeth etc. are reflected in the resulting parameter. The envelope of the signal, as opposed to the measured signal is less sensitive to the slow-changing phase shift, which allows obtaining accurate results for the comparison of the respective segments. The inclusion of a square envelope further enhances the sensitivity of the method to small changes in the signal. Developed diagnostic parameter, called Envelope Contact Factor (ECF) is a new time signal calculated as the difference between the squares of the envelope waveform of the signal for the related segments of adjacent teeth contacts at subsequent times.

$$ECF(t) = \left|A^2(i,t) - A^2\left(i-1,t\right)\right| \tag{4}$$

where i–1 and i are numbers of consecutive signal segments. Time symbol t existing in equation (4) should be treated conventionally. It means further samples of the signal in the respective segments.

ECF is the energy parameter emphasizing changes in cooperating teeth, due to differences in meshing forces in neighbouring contacts, as a result of pitch errors, differences in the stiffness of the teeth and any inaccuracies of manufacturing of shafts and gears. Differences in tooth contacts result in a growth of the teeth dynamic loading and resulting stress growth. The higher the volatility index, the more loaded is appropriate pair of teeth and the greater the probability that damage will occur at this place. Parameter ECF due to the fact that it is a differential parameter is insensitive to slow the changes in the signal, and is very well suited for the detection of signals containing pulse-type changes that often occur in the case of pitting and breaking gear teeth. Its calculation is very fast, because it can be obtained by moving the cyclic data buffer corresponding to the entire rotation of the shaft of one segment of the signal (i.e. the first segment becomes final), and subtracting the two buffers from each other.

$$ECF(t) = \left|A^2\left(t-\tau\right) - A^2(t)\right| \tag{5}$$

where τ is the time shift corresponding to the transverse radial pitch.

While calculating the ECF index in this way one does not have to divide the signal into segments. What is important is that the length of the sample corresponding to the averaged rotation of the shaft was divisible by the number of teeth on a gear mounted on this shaft. This means adopting the same length for each segment corresponding to transverse radial pitch.

Figure 4 shows changes of the ECF index for the last 40 minutes of the experiment lasting 72 minutes calculated for the envelope of the signal. Exactly the same results were obtained substituting envelope with TKEO operator.

5. Conclusions

The proposed methods, in part relate to the differential transforms (e.g. Teager-Kaiser Energy Operator), show that it is possible to trace the source of diagnostic information without the use of commonly used integral transforms. These methods allow the identification of the type of defects and their location, both in terms of damage of the individual shafts (e.g., the appearance of eccentricities, or damage of the coupling), as well as damage to the individual teeth of the pinion or wheel. They refer directly to the time signals bypassing the most complicated procedures of integration. Their advantage is the simplicity and speed of action of great significance for their implementation in autonomous diagnostic systems of gears [30] and diagnostic systems working online.

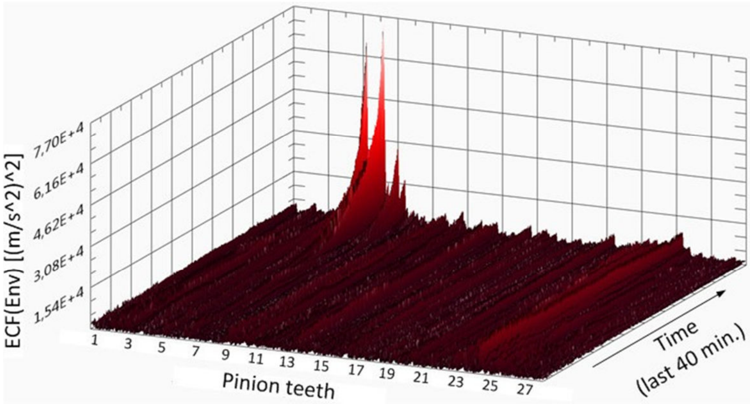

Figure 4. ECF signal for the last 40 min. of the experiment (total of 72 min.)

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