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VIBRODIAGNOSTIC METHOD FOR DETERMINATION OF THE STATE OF WEAR OF HCR GEAR SETS

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Abstract

The paper is aimed at presenting the basic procedure and methods used for the determination of the state of wear of HCR (High Contact Ratio) gear sets by means of vibro-acoustic diagnostics. After the study and calculation of characteristic frequencies, the author experimentally measured the dynamical behaviour of the gear sets to determine their frequency spectra, as well as to carry out cepstrum analysis. Experiments were carried out on an FZG test gearbox equipped with HCR test gears during one lifecycle. Each frequency spectrum and cepstrum was assigned to a specific percentage occurrence of pitting. Analyzed resulting values of amplitudes of mesh frequency components and their sidebands (and corresponding quefrencies) in the spectrum (and cepstrum) were compared and the state of wear was assigned to each frequency (quefrency) response. The results indicate, that also by means of FFT analysis the incubational time interval of the gear fault can be determined, which is not possible using classical methods.

1. INTRODUCTION

Vibro-acoustic diagnostics is an effective non-disassembling method used in mechanical engineering for investigation of the symptoms and syndromes aimed to find the fault of the machines, machineries, or mechanical systems. The vibro-acoustic signal that is sensed carries in its amplitude characteristics information about all the changes of the system of the ideal state. By the means of diagnostics there can be detected the problems (deviations from normal conditions), diagnosis of the faults and their causes, prognosis of future fault progression, recommendation of actions and quality of products.

As far as the prognosis of machine health is concerned (which demands prophecies of future machine integrity and deterioration), there can be no exactitude in the process requiring the statistical or testimonial approaches to be adopted. Investigation in prognosis of machine health therefore embodies guidelines, approaches and concepts rather than procedures of standard methodologies.

Prognosis of future fault progressions requires foreknowledge of the probable failure modes, future duties to which the machine will/might be subjected, and a thorough understanding of the relationships between failure modes and operating conditions. This can demand the collection of previous duty and cumulative duty parameters, along with condition and performance parameters, prior to extrapolations, projections and forecasts.

Also, there are a growing number of models for damage initiation and damage progression. Prognosis processes need to accommodate these and future analytical damage models.

As computing power increases and multiple parameter analysis becomes a reality, the ability to predict the initiation of a failure mode is not inconceivable if the initiation criteria, expressed as a set of parameter values for a given mode, are known as well as their future behaviour for a given set of conditions.

The level of the gear damage (e.g. pitting occurrence and/or thermal scuffing) is determined in idle state by means of optical investigation and measurements of percentage of damaged area of mashing tooth area [4, 6].

2. TESTING DEVICE

For the determination of the state of wear of HCR gear sets, the FZG back-to-back gear test ring has been used. The standardized device (DIN 51 354 [5]) serves to investigate the load carrying capacity, which is limited by pitting, micro-pitting, thermal scuffing, slow speed wear or tooth breakage. The schematic drawing as well as figure of the used device is shown in the Figure 1.

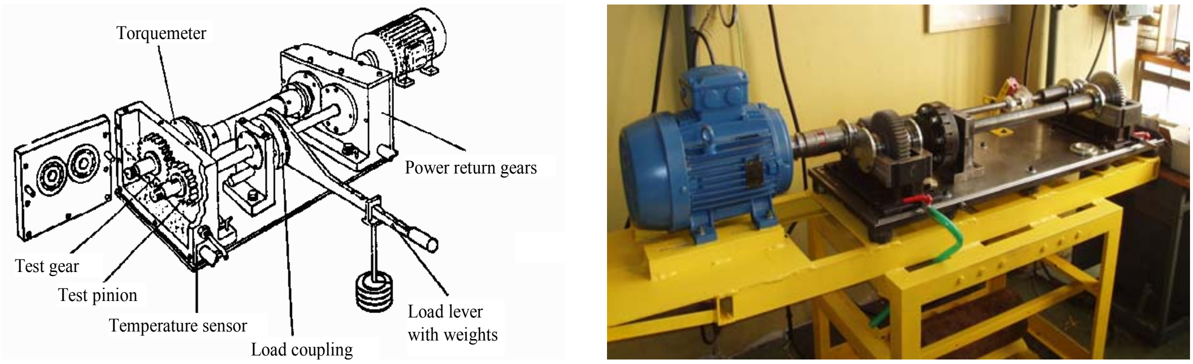


Figure 1. The FZG device (Niemann’s gearbox – left) that was used, installed in the laboratory before measurements (with open gearboxes – right).

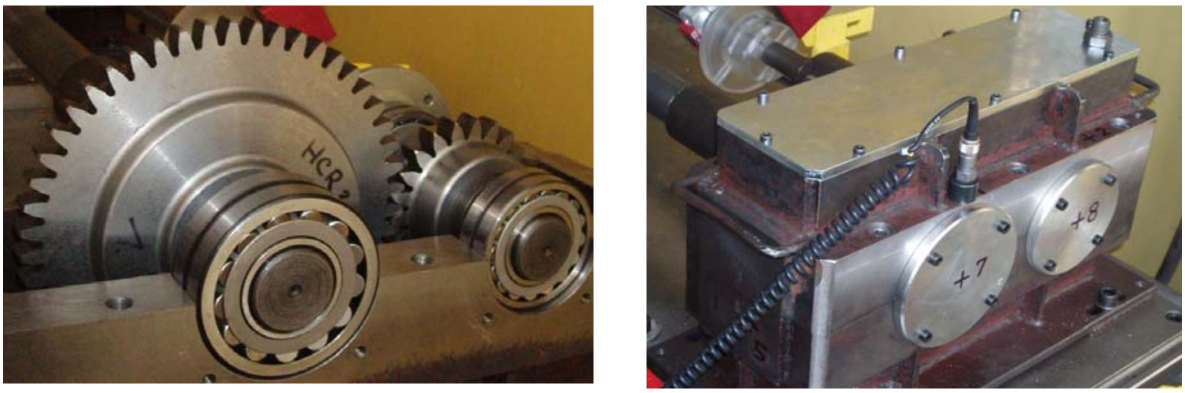


Figure 2. Detail on investigated HCR gear wheels.

It consists of two gearboxes (one equipped with investigated, second one with auxiliary gearwheels). Gearboxes are connected with two shafts. The loading of the system is ensured by the pre-stress of the shaft set using load coupling. The power is delivered by an electromotor.

Both gearboxes are equipped with the HCR (High Contact Ratio) spur gearwheels (no. of teeth 21, 51, respectively, Fig. 2). The difference from a commonly used gears is a higher value of contact ratio – $\varepsilon_\alpha = 2.003$. This type of gear provides higher contact area and therefore the higher life length and also lower noise level is ensured [9].

3. DETERMINATION OF GEAR FAULTS

When the frequency analysis of the new well produced gearbox is carried out without any manufacturing faults, the excessive amplitude of allowable imbalance of gearwheels (rotational frequency of shafts with gears), mesh frequency (1st, 2nd and 3rd harmonics) with smaller amplitudes of side bands with interval of the rotational frequency of the gear sets, and faults of load coupling (imbalance – 1st harmonics of shaft rotational frequency) can be determined.

The difference of profiles from the ideal profile is the main reason of the new gear vibration. It can be caused due to loading or geometrical deviation. The mesh frequency is dominating in well produced, as well as at faulty gearboxes. It is defined as

$$f_z = f_0 z \tag{1}$$

where f_z and f_0 is the mesh frequency and rotational frequency, respectively and z is the number of teeth.

The pitting and/or state of wear produced sidebands about the mesh frequency and its harmonics in the frequency domain. If the rotational frequencies are f_{01}, f_{02} and mesh frequency is f_z, then sidebands frequencies are [7]

$$f_{p1} = f_z \pm n f_{01} \tag{2a}$$

$$f_{p2} = f_z \pm m f_{02} \tag{2b}$$

where $n, m = 1, 2, 3, \ldots$

When the fault on the gear start to occur the ideally sinusoid signal in time domain is deformed. In the frequency domain this change will be more visible in the higher harmonics. Therefore it is useful to analyse at least the first three harmonics of the mesh frequency.

The sidebands, which occur in the vicinity of the meshing frequency, can be explained as a modulation of the frequency. The change in vibration behaviour and consequential amplitude modulation shows the dependence of tooth deformation on external dynamic loading. If the signal at the meshing frequency is distorted, the sidebands will start to occur.

The distribution of the sidebands around the mashing frequency is given by modulation frequency. Therefore it gives useful information about behaviour of the gear or pinion faults.

The mesh frequency and its harmonics have more energy than the frequencies of starting faults, and therefore the progressive fault development can be observed as an increment in higher harmonics of mesh frequency (2nd and 3rd harmonics).

The level of the state of wear can be determined by comparing the characteristic frequencies according to the following criteria:

- the ratio of the peak value of the amplitude to its RMS value;
- the ratio of total energy of mashing frequency harmonics to energy of fundamental mesh frequency;
- the ratio of total energy of noise frequencies (or sidebands) to energy of fundamental mesh frequency [1, 4, 7, 8].

4. RESULTS AND DISCUSSION

The first set of measurement was focused on the comparison of frequency spectra (peak values of characteristic frequencies, Tab. 1). For the elimination of random influences, the averaging of 50 frequency spectra for each measurement was done.

Table 1. The characteristic frequencies.

Type	**Frequency** (Hz)
Shaft frequency no.1	12,4
Shaft frequency no.2	5,2
Mesh frequency	261,3

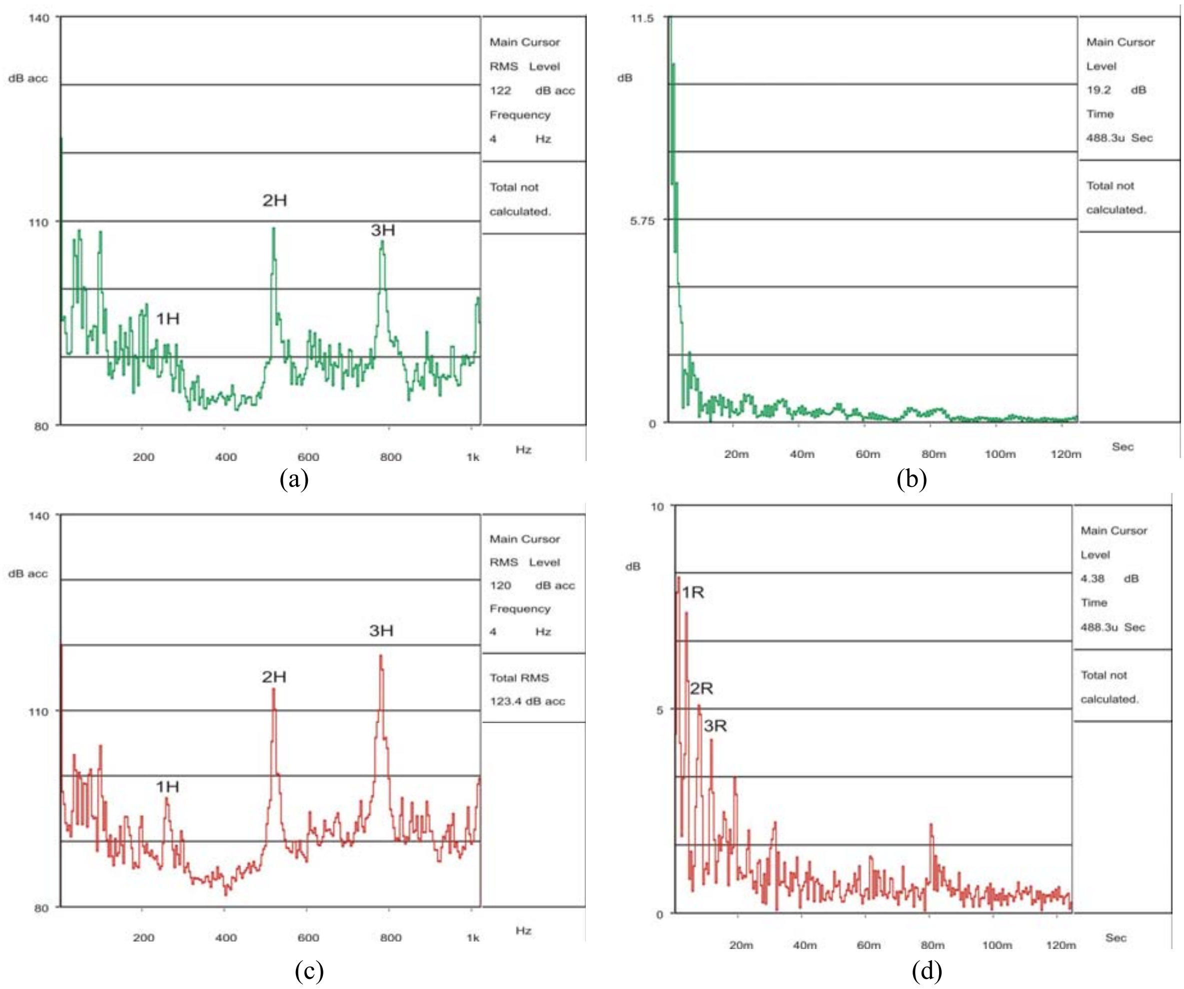


Figure 3. (a), (b) Frequency spectra and cepstrum of the new gear sets, respectively; (c), (d) Frequency spectra and cepstrum of the gearing with occurrence of pitting.

The spectra and cepstrum of new gearwheels are depicted in the Figure 3a and 3b, respectively. The frequencies of imbalance and misalignment are present in the low frequency region. The first harmonics of mesh frequency is in the level of noise, whereas second and third harmonics are significant in the frequency spectra. From the cepstrum analysis is obvious, that the sideband does not occur.

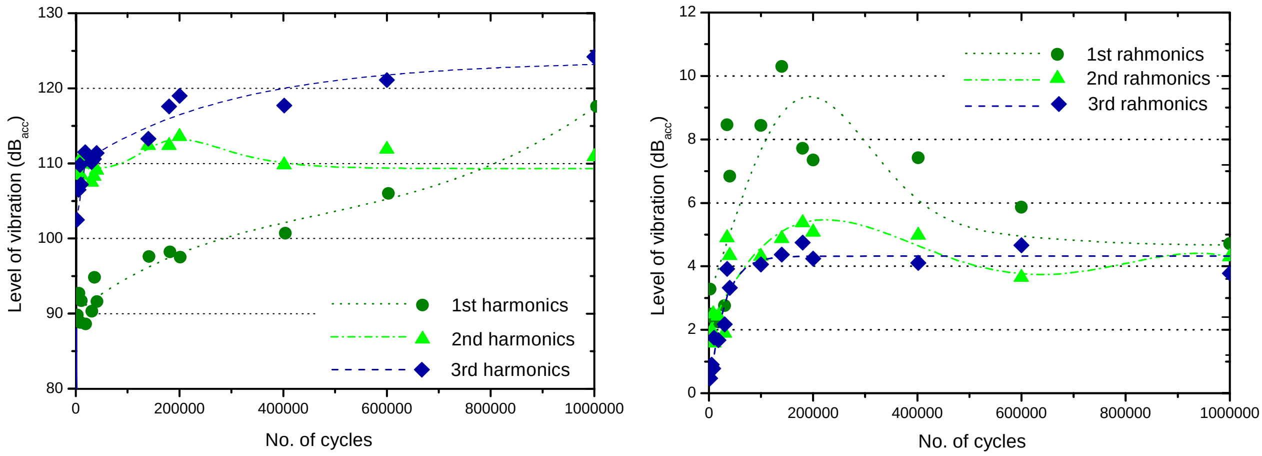
During the one life cycle of the gearwheels, regular measurements of frequency spectra were carried out.

In the Figure 3c and 3d are shown the frequency spectra and cepstrum of the gear sets, when the pitting occurres. In the frequency spectra we can notice the increase of all three mesh frequency harmonics. The cepstrum provides useful the information about the increase of sideband amplitudes.

The trend characteristics of harmonics as well as rahmonics behaviour within the life cycle were evaluated by means of Origin software. The fitting functions were used for predefined relations, mostly of exponential behaviour. For more precise fitting, the step between measurements should be smaller (e.g. each 50 000 cycles if we want to reach 1 000 000 cycles).

The trend functions show an exponential growth of the harmonic frequencies with pitting extension (Fig. 4a). The 2nd harmonic frequency reaches a peak value at 200 000 cycles when the pitting has been observed. The trend lines show the growth of first three harmonic frequencies corresponding with pitting and thermal scuffing failure development.

More significant peak values are visible in cepstrum analysis (Fig. 4b). As the fault starts to occur, the amplitude of first rahmonics rises, after reaching certain resulting value of the state of wear the trend will change and the amplitudes will start to decrease. The rise of the amplitude is caused by the development of failure; the fall of the amplitude after 200 000 cycles is caused by running in of the gear wheels which were damaged by pitting and thermal scuffing.



(a) (b)

Figure 4. Trend characteristics of (a) harmonics and (b) rahmonics (sideband of shaft 1) behaviour when pitting starts to occur.

6. CONCLUSIONS

The operating gear systems are exposed to different types of wear. Some of them, e.g. pitting of crack at the tooth base, is the result of fatigue, some of them occur in short time interval (thermal scuffing). Nowadays they more often occur in gear systems (mainly automatic gears) involute HCR gear sets, where the known failures are presented in different ways compared to standard gear profiles. It is valid predominantly for pitting and thermal scuffing.

To determine these types of failure is possible only after disassembling of the gear system. This quantitative evaluation takes a long time and it is economically demanding. If a non-disassembling diagnostics would exist, it would minimize the costs of maintenance and running costs of the gear systems [1, 2, 3].

The first set of results shows us that the way of investigation of gear failure level (due to pitting and thermal occurrence of scuffing) is real and possible to use and has many advantages compared with widely used classical methods. The results indicate, that also by means of FFT analysis the incubational time interval of the gear fault can be determined, which is not possible using classical methods.

The measurements show possible methodology, which have to be proved by subsequent measurements on the same gearwheels. The process of the damage progress with respect to the spectrum and cepstrum characteristics is the second answer that is being sought. The work continues with measurements on the same type of gear sets to obtain wider knowledge base for statistic analysis of the measurements.

Evaluation of the experimentally measured values is assumed to use regression analysis, statistics analysis, probability analysis and the Monte Carlo method.

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