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CLASSIFICATION OF TOOTH GEAR WHEEL FAULTS OF GEARBOX WORKING IN THE CIRCULATING POWER TEST RIG BY MULTILAYER PERCEPTRON AND CONTINUOUS WAVELET TRANSFORM

Abstract:
In the article the results of the attempts are presented to build a classifier of the local teeth damages in gear wheels, based on artificial neural networks. In the tests the neural networks of a multilayer perceptron type (MLP) were used. The research object was a toothed gear with straight teeth, working on a rotating power stand FZG. Both the undamaged gears and gears with local teeth damages in the form of crack in the tooth base and the crumbling of a tooth tip were tested. In the article, it is suggested to build a descriptor of wheel teeth local damages with the use of vibration signals which were properly filtered and processed.

Keywords:
gearbox, diagnosis, neural networks

INTRODUCTION

Monitoring and diagnosing the state of technical objects is one of the basic actions in the construction of a strategy for their proper exploitation. Very often, when a failure occurs, not only is it connected with economic loss, but also with danger to human life. It is necessary, then, to create the proper diagnostic tools enabling the early detection of all the threats. The tests conducted for many years, both in national and foreign research laboratories, are aimed at creating proper tools, helpful in the recognition process of the power transmission system damages [1-6,8-11,13-15,17]. Currently, all over the world, methods are developed to enable the diagnosis of the condition of the drive transfer system elements without the need of their disassembly.

Among such methods we find the vibroacoustic method, where the sources of information about the object condition are the vibrations and/or noise emitted by it. Literature points at huge possibilities of vibroacoustic signals use in the diagnostic process and their proper filtration, preliminary processing and analysis allow getting information about the object condition. Novelty described in literature is an expert system which uses the artificial intelligence elements [5-9,12-14,16]. Properly constructed and taught system can automatically recognise the occurring defects.

RESEARCH OBJECT

The research object was a toothed gear working in the power transmission system, which consisted of an electric engine, belt transmission, *tested toothed gear, closing gear and stretching clutch. The electric engine with a power of 15 [kW] with the use of belt transmission powered the closing gear. The gear load was regulated by the levers with weights, stretching clutch and torsional shafts. The work speed of the gear was set with the use of frequency converter steering the work of the electric engine. The tested gear and the closing gear had the same transmission ratio and the same wheel base.*

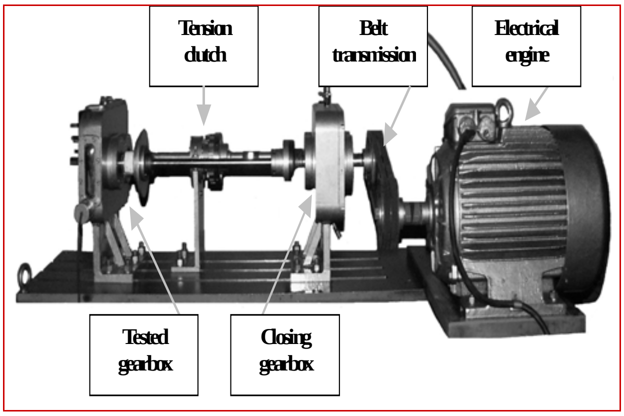

Fig. 1 Scheme of the circulating power test rig

In fig.1 the tested toothed gear is presented working in the rotating power system.
The toothed gear with straight teeth was tested, where the number of teeth in the pinion and the wheel equalled 16 and 24 respectively. In the tests the toothed wheels made of 20H2N4A were used, which were carburizated and hardened to the hardness equalling 60-62 HRC.

THE EXPERIMENT DESCRIPTION

The aim of the experiment was an attempt to classify the type and stage of teeth damages in gear wheels with the use of artificial neural networks [5-9,12-14,16].
In the experiments it was decided to use the diagnostic information about the object condition included in the vibration signal. On the basis of literature [2-6,9-11,13-15,17] the signal assumed as the information carrier correctly reflecting the damages of toothed gear was the transverse vibration speed signal of the wheel shaft. The measures were taken in the direction of inter-teeth force interaction.
The measurement system consisted of angular position sensors of shafts, a logic unit, a laser vibrometer, the signal analyser and a computer. The measurement of the transverse vibrations of the gear wheel was conducted with the use of laser vibrometer Ometron VH300+. The logic unit with two angular position sensors of shafts enabled the precise definition of the connection moment of the same pair of teeth. The registered vibration speed signal and the reference signal from the logic unit were processed in the signal analyser DSPT SigLab. The measured signals were sampled with frequency of 25600 [Hz] and registered on a PC computer.
In order to check the functioning correctness of the neural classifiers in the task of defect stage identification of the toothed gear, a series of transverse vibrations measurements was conducted of the wheel shaft in an undamaged gear and in a gear with modelled damages:
- *cracks at the tooth base (1 and 3 [mm]),*
- *crumblings on the tooth tip (0,75 and 1,5 and 2 [mm]).*

The measurements were conducted for a toothed gear working at two rotational speeds of the wheel shaft (900 and 1800[obr/min]) and with two loads (138 and 206 [Nm]).
The result of the conducted process of signal registration was the achievement of the matrix consisting of 971 transverse vibrations speed signals of the wheel shaft.
The vibration signals registered on FZG stand were put under the influence of five filters. Filters number 1 and 2 were low-pass filters with the range of 6 and 12 kHz. Next filters enabled getting the residual signals (filter number 3) and the differential signals (filter number 4). The last filter enabled getting the signal of meshing frequency range from 0.5-1.5 [5,6,9-11].
Signal in time domain, known as residual signal was achieved by the removal from the spectrum of bands including the rotational constituents of the wheel shafts and their harmonics and the constituents of the meshing frequencies and their harmonics, and next by the use of the inverse Fourier transform. The differential signal was achieved similarly to the residual signal, but in this case the removed bands around the meshing frequency and their harmonics were wider and included the sidebands connected with the rotational frequencies of the toothed wheels.
In the next stage of tooth damage models creation the vibration signals achieved with the use of five filters were put under the influence of continuous wavelet transform (CWT) [1,4-6,8,13,15].

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Wavelet analysis consists of signal decomposition and presenting it in the form of linear combination of basic functions, called wavelets. The feature which distinguishes this method of signal analysis from other methods is the multi-stage signal decomposition, variable resolution in time and frequency domain and possibility to use basic functions other than harmonic functions. Continuous wavelet transform is defined as follows:

$$\mathrm{CWT}(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}\psi\left(\frac{t-b}{a}\right)\cdot x(t)dt \qquad (1)$$

where:

$\psi_{a,b}(t)$ *– the analyzing wavelet,*

a *– the scale parameter,* $a \in R^{+}$, $a \neq 0$,

b *– the time parameter,* $b \in R$.

Wavelet frequency is regulated by the parameter of scale a, whereas using parameter b one can test the local properties of the time runs.

This method, due to the possibility of adjustment of the window width to the analysed frequency range enables testing the non-stationary signals. For the long-term variation runs the window expands in time domain, whereas with high frequencies it narrows preserving a constant surface area. The authors in paper [8] states that the proper choice of the basic wavelet and the array of the scale value determine the correctness of the diagnosis process of the object technical condition with the use of wavelet analysis.

In the preliminary test the usefulness of 83 basic wavelets was checked, which belonged to series: haar, daubechies, biorthogonal, coiflets, symlets, morlet, mexican hat, meyer, reverse biorthogonal, gaussian, complex gaussian, shannon, frequency b-spline, complex morlet, discrete approximation of meyer.

In order to describe the change character of the signal amplitude under the influence of CWT for 20 scale analyses, chosen in preliminary stage, a measure was marked. This measure described the change course of the amplitude CWT distribution in time domain. In the tests the usefulness of 35 diagnostic measures commonly used in literature was checked (variation coefficient, peak coefficient, clearance coefficient, shape coefficient, impulsing and asymmetry coefficient, quarter and average deviation; arithmetic, geometric and harmonic averages; quartiles, non-dimensional discriminants, central moments, cumulants, signal energy, efficiency values, inter-peak values, maximum and minimum, variance, positional variation coefficient) [5,6].

As a result of tests 14525 sets of models were built. Each set of models had the size of 971x20. This size reflected the number of cases (number of measured on FZG stand vibration signals) and the number of network inputs (number of scales, in which the measure was marked). Each option of model sets was divided into halves and it this way teaching and testing data were achieved.

In preliminary investigations were chosen following wavelets [5,6]:

- *Daubechies Wavelet 9 (wavelet no. = 9),*
- *Morlet Wavelet (wavelet no. = 37),*
- *Reverse Biorthogonal Wavelet 3.7 (wavelet no. = 50),*

and estimators [5,6]:

- *impulse ratio (estimator no. = 5),*
- *root mean square (estimator no. = 14),*
- *value of range between maximum and minimum (estimator no. = 25).*

In the tests performed in order to build a diagnostic classifier the artificial neural networks of multilayer perceptron type (MLP) were used.

In case of application of such neural networks, one needs to define the architecture, the method of network teaching and the type of neurons used in hidden layers of the network [7,12,16]. It should be remembered, however, that the stages should not be divided, because they are directly connected. At the same time literature shows the lack of rules connected with the choice of the parameters and points out the necessity of their setting with the use of experimental method – trial and-error method [7,12,16].

In the conducted experiments for each set of models the best option of network architecture was chosen. By the selection of network architecture the usefulness of classifiers build of one and of two hidden layers was checked. On the basis of preliminary tests [5,6] it was assumed that for each hidden layer there is a possibility of existing of 5, 10, 15, 20, 25 and 30 neurons. Simultaneously, an attempt was made to check, if for an analysed diagnostic task an optimum architecture can be defined, independently from the way models are built.

Next element, which was supposed to be defined, was the kind of the applied teaching method. By its choice one should take into account both the criterion of the error value, as well as the time requirements needed for network teaching. At the same time it should be noticed that the efficiency of the teaching methods is dependent on: the particular task, the number of the accessible models and the network architecture. That is why it is not possible to decide a priori, which method is the most efficient one. In the tests it was decided to check the usefulness of different network teaching methods (Table 1).

Tab. 1: MLP network teaching methods.

No	Name of algorithm
1	Gradient descent backpropagation
2	Gradient descent with momentum backpropagation
3	Gradient descent with momentum and adaptive learning rate backpropagation
4	Resilient backpropagation
5	Conjugate gradient backpropagation with Fletcher-Reeves updates
6	Conjugate gradient backpropagation with Polak-Ribiere updates
7	Conjugate gradient backpropagation with Powell-Beale restarts
8	Scaled conjugate gradient backpropagation
9	One step secant backpropagation
10	BFGS quasi-Newton backpropagation
11	Levenberg-Marquardt backpropagation
12	Bayesian regularization backpropagation

It was checked what influence the applied algorithm of network teaching has on the correctness of the achieved results.

In each of the experiments two types of neurons used in hidden layers were checked. For the tests sigma neurons and tangent curve type neurons were chosen [7,12,16].

THE RESULTS OF THE EXPERIMENT

In the first trials it was decided to build an artificial neural network capable of recognition of the following classes of damages:

- *an undamaged gear,*
- *a gear with a tooth cracked at its base,*
- *a gear with a crumbled tooth.*

Tests with the use of MLP type classifiers taught with the use of data gathered in CWT analysis led to construction of classifiers characterised by the error-free diagnosis of the damage type in a toothed gear. Independently from the neuron types used in the hidden layers of the MLP network, the lowest classification error values were achieved in case of application of the effective value (number of measure = 14) to the description of change character in the CWT distribution. The highest error values of classifiers diagnosing the type of gear teeth damages were achieved with the use of methods number 1, 2, and 3 in the teaching process (Table 1).

Because it was possible to build a classifier, which could faultlessly assess the type of the existing teeth damage of the gear wheels, it was decided to proceed to the research target in further experiments, that is to the task of checking the MLP network usefulness in the classification process of teeth damage type and advancement in gear wheels. In the conducted tests the neural network of MLP type was taught to identify the following classes:

- *no damages,*
- *crack at the tooth base at a depth of 1 [mm],*
- *crack at the tooth base at a depth of 3 [mm],*
- *0,75 [mm] crumbling of the tooth tip,*
- *1,5 [mm] crumbling of the tooth tip,*
- *2 [mm] crumbling of the tooth tip.*

The results of the conducted experiments aiming at the choice of optimum architecture of MLP network showed the relationships resulting from the extension of the number of neurons. Some cases were noticed, where with the rise of the neurons number in first hidden layer, the error initially drops and then rises. It occurs due to the fact that the network was over-taught and lost the ability to generalise. Such situations are also visible, where the increase in the number of hidden layers with the appropriately big number of neurons improves the efficiency of the classification.

On the basis of the achieved results one can notice, that independently from the used teaching algorithm of a network, type of neurons applied in hidden layers and the chosen basic wavelet, the lowest testing error level appeared in case of classifiers taught on data achieved from the CWT distribution characterised with the use of effective value (measure number = 14). The highest testing error level was visible with the use of inter-peak value (measure number = 25).

It can be noticed during the analysis of the classification results with regard to the filtration method of the vibration signal used during models creation that independently from the used algorithm of network teaching, the types of neurons applied in hidden layers and the chosen basic wavelet the least precise classifiers were created on the basis of the residual signals and the differential signals (filter number 3 and 4).

Neural networks taught with the use of gradient method showed big sensitivity to the neurons type used in hidden layers. By application of models created in the same way in the teaching process, the classifiers built of tangent neurons distinguished themselves with a far better level of results consistence with the model, than the classifiers built of sigma neurons. Such dependence did not occur in case of networks taught with the use of Levenberg-Marquardt method.

CONCLUSIONS

As a result of the conducted research it was possible to build a correctly working classifier of both the kind, as well as the kind and advancement of the gear damage.

On the basis of the conducted research one can notice, that a significant influence on the achieved classification error is exerted both by the way of damage models preparation (filtration method, type of applied basic wavelet, applied measure) and by the architecture and the artificial neural network teaching method.

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