GEAR FAULT DETECTION USING VIBRATION ANALYSIS

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Summary

The article includes results of the team's research work on vibroacoustic diagnostic of gearbox components' faults. A review of simulation and experimental researches that aimed at elaboration of methods which would enable early identification of teeth faults in the form of working surface pitting, spalling of tooth crest, crack at the tooth bottom as well as partial breaking of a tooth, is presented. Assessment of selected methods of processing the vibroacoustic signals during the detection of gear faults has been carried out while faults occur in gear bearings working under various conditions. The initially processed vibration signals analyzed within time and frequency domains constituted a basis for preparation of detection measures that were sensitive to early stages of damage. The measures obtained as a result of simulation and experimental tests were used to construct a set of neuron classifier models to diagnose the type and degree of toothed wheels faults with a validation error below 5%. The achieved qualitative and quantitative conformity of simulation and experimental research results has shown that application of an expanded and identified dynamic model of the gear in a power transmission system enables the acquisition of reliable diagnostic relations.

Keywords: gearbox, vibration, gear fault, diagnostics.

WYKRYWANIE USZKODZEŃ PRZEKŁADNI NA PODSTAWIE ANALIZY DRGAŃ

Streszczenie

W artykule zawarto wyniki prac zespołu w zakresie diagnostyki wibroakustycznej uszkodzeń elementów przekładni zębatych. Przedstawiono przegląd badań symulacyjnych i doświadczalnych, których celem było opracowanie metod pozwalających na wczesną identyfikację uszkodzeń zębów w postaci pittingu powierzchni roboczych, wykruszenia wierzchołka, pęknięcia u podstawy zęba oraz częściowego wyłamania zęba. Dokonano oceny efektywności wybranych metod przetwarzania sygnałów wibroakustycznych w procesie wykrywania uszkodzeń kół zębatych przy jednoczesnym występowaniu uszkodzeń łożyskowania przekładni pracujących w różnych warunkach. Wstępnie przetworzone sygnały drganiowe analizowane w dziedzinie czasu i częstotliwości stanowiły podstawę do opracowania miar diagnostycznych wrażliwych na wczesne stadia uszkodzeń. Miary otrzymane w wyniku symulacji oraz badan doświadczalnych wykorzystano do budowy zestawu wzorców klasyfikatora neuronowego diagnozującego rodzaj i stopień uszkodzenia kół przekładni z błędem walidacji poniżej 5%. Uzyskana zgodność jakościowa i ilościowa wyników badań symulacyjnych i doświadczalnych wykazała, że wykorzystanie rozbudowanego i zidentyfikowanego modelu dynamicznego przekładni w układzie napędowym umożliwia pozyskanie wiarygodnych relacji diagnostycznych.

Słowa kluczowe: przekładnie zębate, drgania, uszkodzenia kół, diagnostyka.

1. INTRODUCTION

Toothed gears are designed for cooperation with sources of propulsion of higher and higher power and are exposed to high external dynamic loads. In the design process, designers are trying to achieve the highest possible ratio of power transmitted through wheels to their weight. A gear working under high load should be either sporadically or constantly monitored to ensure safe operation. The techniques of diagnosing the technical condition of gears are oriented towards identification of faults of their components in the initial phase of fault occurrence.

One of the most frequently applied methods is measurement of the vibroacoustic signal and on this basis, determination of measures sensitive to different types of damage.

The rate of propagation of vibroacoustic disturbance caused by a changed condition of a gear makes the vibroacoustic methods particularly useful in diagnosing early stages of faults.

Recently, techniques of contactless measurement of vibration have developed considerably. They enable measuring the vibration speed of rotating bodies. Measurements of the vibration speed of rotating shafts make it possible to eliminate the consequences of complex and variable in time transmittance of the bearing/gearbox system, which allows obtaining effective symptoms of faults.

An essential issue in the diagnosing of gearboxes is the ability to differentiate between various phenomena influencing the vibroacoustic signal connected with both, normal operation of the gearbox and development of faults in its components.

Toothed wheels and bearings are the gearbox components most susceptible to damage. The modern diagnosing methods of gearboxes are oriented to the detection of early phases of fault occurrence, e.g. spalling of tooth crest, crack at the tooth bottom, fatigue chipping of the upper layer, or galling of the interacting surfaces. In the diagnosing of rolling bearings, detection of initial stages of damage to the bearing race or rolling elements is extremely important.

The development of computer hardware and signal processing methods enables using advanced signal analysis methods in the time-frequency plane. The methods allow observation of non-stationary impulse disturbance induced by faults in their initial stages.

Experimental research on gearboxes is difficult to carry out, as well as costly and time-consuming, and in the case of gears produced as single items, most often impossible. In such cases, it is justified to use an identified dynamic model of a gear in a power transmission system [5]. Such model will allow making a series of numerical experiments and analysis of the simulation results will enable expanding the diagnostic knowledge and obtaining higher certainty of the diagnosis.

For the monitoring of the condition of many power transmission units, expert systems are created, which use artificial intelligence components. A properly constructed and taught system can automatically recognize the existing faults. Neuron networks in the process of learning acquire the ability of generalizing knowledge, which allows detection of faults in their early phases, often not noticed during diagnosing. A basic problem while constructing such systems is to define a set of input data and acquire an appropriately large set of training data [1].

2. SIGNAL ANALYSIS METHODS IN THE DIAGNOSING OF GEARBOXES

In vibroacoustic diagnostic of gearboxes, a number of different signal analysis methods are used [2, 6, 7, 13, 14]. Figure 1 presents a general classification of the existing signal processing methods. The basis consists of a properly selected vibroacoustic signal (WA) which, in order to eliminate incidental disturbance, can be synchronously averaged and from which, by applying appropriate filtration, a differential and residual signals are obtained, as well as a signal containing only bands of meshing frequency and its harmonics. On the basis of the first two signals, numerical estimators of amplitude and dimensionless discriminants are calculated. Analysis methods are used in time domain, frequency domain, or in time and frequency domain, as well as statistical moments of higher orders. Those dimensionless discriminants which are based on statistical moments of higher orders (FM4, M6A, M8A, NA4 ...) are most often determined using differential and residual signals [1, 4, 10, 12].

In case of simultaneous occurrence of faults in wheels and bearings, it is justified to apply comb filtration, thus enabling separation of vibration signals generated by different faults [9].

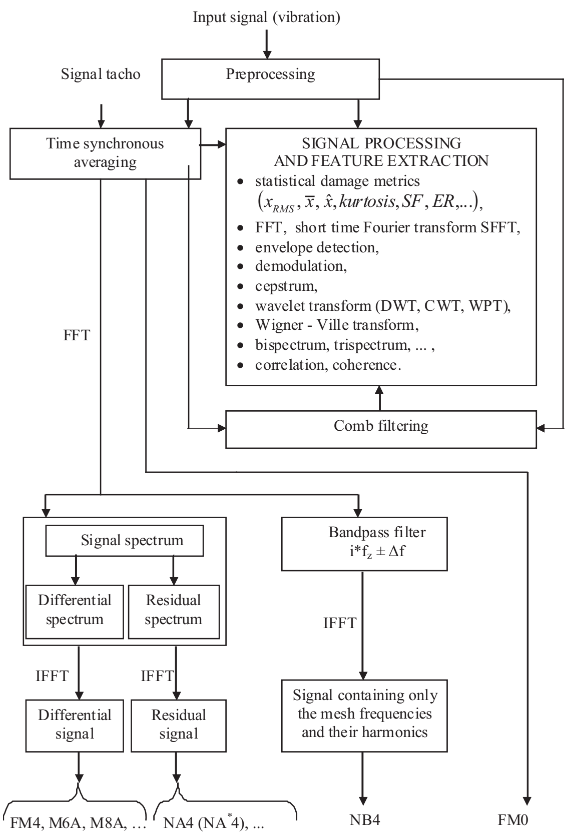

Fig. 1. Methods of vibroacoustic signal processing.

3. MODEL OF TOOTHED GEAR WORKING IN A POWER TRANSMISSION SYSTEM

In the simulation tests, a dynamic model was used representing a toothed gear working in a power transmission system (Fig.2). The model was created in the *Matlab–Simulink* environment. It takes into account the characteristics of an electric driving motor, single-stage gear, clutches and working machine.

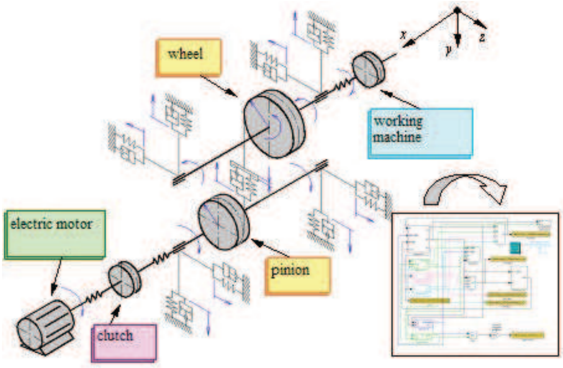

Fig. 2. Dynamic model of toothed gear in a power transmission system.

The simulation model allowed taking account, in the calculations, of cyclic and random deviations which occurred in the mesh [3, 5, 11].

The utilization of a dynamic model of gear in a power transmission system was possible owing to very good identification and tuning of the model parameters. It gave very high qualitative and quantitative consistency of simulation results with the results obtained from tests of a real object [1, 5, 6, 9].

The gear model also enabled mapping of local faults consisting of a crack at the tooth bottom or chipping of tooth crest, and faults of rolling bearings' components.

The chipping of tooth crest throughout its length was modeled as tooth contact section shortened by a value equal to a predetermined part of pitch. The effect of a changing tooth contact section length on the meshing time was taken into account as well. Chipping of tooth crest in a pinion results in a premature finish of operation by a couple of teeth, whereas chipping of the reference cone apex results in a delayed start of cooperation between the couple of teeth.

A crack at the tooth bottom is accompanied by reduced rigidity of meshing. Therefore, a fault of this sort was mapped as a percentage reduction of rigidity of the cooperating couple of teeth in relation to a couple without faults.

Analysis of the effect of the crack depth in the tooth root on a change in mesh rigidity was presented in monograph [9].

Faults of working surfaces of cooperating elements of rolling bearings were modeled in a similar way, by reducing the bearing rigidity while the damaged piece of surface was in the load transmission zone [9].

4. DETECTION OF TOOTH CREST CHIPPING

Initial phases of tooth crest chipping development in a toothed gear do not significantly influence the general level of vibration. Hence, detection of damages of this type in the early phase is very difficult. It appears from the previous research that the use of a contactless laser measurement of transverse vibration speed of rotating gear shafts, combined with advanced methods of signal processing, such as Wigner-Ville distribution or continuous wavelet transform, enables detecting such fault in its initial stage. This method of measurement eliminates the influence of complex transmittance of the bearing - gear casing system [9].

Fig. 3 shows the results of time and frequency analysis *WV* of differential signal.

In the *WV* distribution, an increase of amplitude occurs within the pinion turn angle corresponding to the cooperation of the damaged tooth.

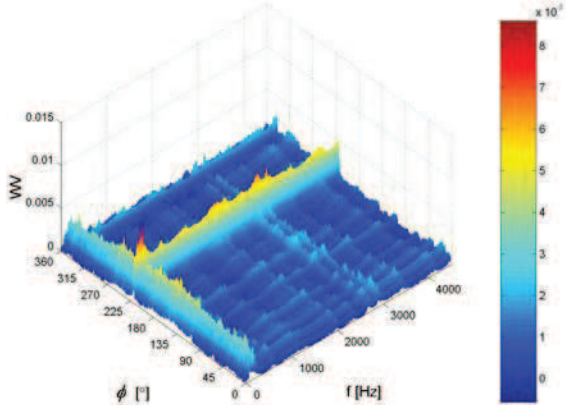

Fig. 3. *WV* Time/frequency distribution of differential signal – measurement of vibration speed of pinion shaft in the direction of the force acting between the teeth – 1 mm chip of the pinion tooth.

For easier interpretation of the results obtained, summation was performed of *WV* distribution discrete values (formula 1) in accordance with the equation:

$$S_{WV}(\phi) = \sum_{k_{WV}=A}^{B} WV(l_{WV}, k_{WV}) \qquad (1)$$

$$WV(l_{WV}, k_{WV}) = WV(t, f) \qquad (2)$$

where:

l_{WV}, k_{WV} – discrete values of time and frequency, respectively,

A, B – discrete values corresponding, respectively, to limit frequencies of the summation interval f_A, f_B.

In the presented in Fig. 4 sum of *WV* distribution, local maxima coming from the chipping of the tooth crest in the pinion are clearly visible, which facilitates localization of the fault.

The sums $S_{WV}(\phi)$ of *WV* distributions, obtained from measurements (Fig. 4) and simulations (Fig. 5) show high consistency.

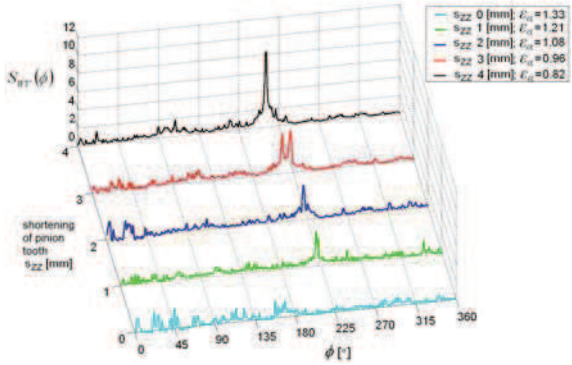

Fig. 4. The sum of time/frequency *WV* distribution in 0÷4500 [Hz] band, generated from a differential signal of pinion shaft vibration speed measured in the direction of the force acting between the teeth – experimental research result.

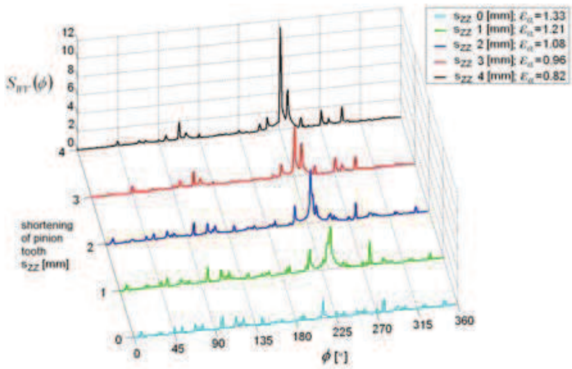

Fig. 5. The sum of time/frequency *WV* distribution in 0÷4500 [Hz] band, generated from a differential signal of pinion shaft vibration speed recorded in the direction of the force acting between the teeth – simulation result.

Based on the research, it can be affirmed that processing of the signal of transverse vibration speed of gear shafts, measured in the direction of the force acting between the teeth, and the use of analyses in, simultaneously, time and frequency, or time and scale domains (CWT), facilitate effective detection of chipping of a tooth crest. Using the sums of WV distribution (Fig. 4, 5) or scalograms [9], measures where built enabling the evaluation of the tooth chip depth.

Computer simulations of a toothed gear with damaged components, made using its expanded and identified dynamic model, made it possible to verify the measures of the case of tooth crest chipping during the operation of gears of different geometrical parameters of toothed wheels, at different rotational speeds, loads or deviations in wheel workmanship.

5. NEURON CLASSIFIER OF TOOTHED WHEEL FAULT

The results of research connected with the structure of neuron classifiers, which were taught and verified on the basis of data obtained from a simulation model of a toothed gear working in a power transmission system, were presented in monograph [1].

For constructing the models, signals of transverse vibration speed of wheel shaft, analyzed by means of *FFT* and *CWT,* were used. Based on preliminary tests, an artificial neuron network of *MLP* type was chosen as the classifier. Sets of models were built on the basis on vibration signals of a toothed gear working in the following conditions:

- $M = 138$ [Nm], $n = 900$ [r.p.m.],
- $M = 138$ [Nm], $n = 1800$ [r.p.m.],
- $M = 206$ [Nm], $n = 900$ [r.p.m.],
- $M = 206$ [Nm], $n = 1800$ [r.p.m.].

A neuron classifier was built, capable of recognizing the degree of fault in wheel teeth in the form of a crack at the tooth bottom or chipping of tooth crest in a gear working at different shaft speeds and different load torques.

It was assumed that the following classes would be recognized:

- a crack at the tooth bottom in the form of percentage reduction of rigidity of a couple of teeth in case of such fault:
  - class 1] 0 ÷ 9 %,
  - class 2] 10 ÷ 19 %,
  - class 3] 20 ÷ 29 %,
  - class 4] 30 ÷ 40 %,
- chipping of tooth crest, in the form of per cent length of pitch, by which the tooth contact section shortens as a result of such fault:
  - class 5] 0 ÷ 9 %,
  - class 6] 10 ÷ 19 %,
  - class 7] 20 ÷ 29 %,
  - class 8] 30 ÷ 40 %,

The training process and the testing validation process are presented in Fig. 6.

When using both, the models obtained from *FFT* analysis and *CWT* analysis, the authors managed to build neuron classifiers which can diagnose the type and degree of fault of a gear wheel tooth with a validation error below 5%.

Irrespective of the model building method, the testing error for data taken from a real gear was ca. 60%.

In the successive stage, apart from data taken from a dynamic model of a gear, part of data coming from tests of a real gear were added to the training set.

The testing error value obtained in that case was ca. 20% in the case where for the construction, layers of both *sigmoidal* and *tangensoidal* hidden neurons were used [1].

The research has shown that it is possible to build a neuron classifier of two fault types of wheel teeth in different stages of advancement for a gear working at different rotational speeds of shaft and with different load torques.

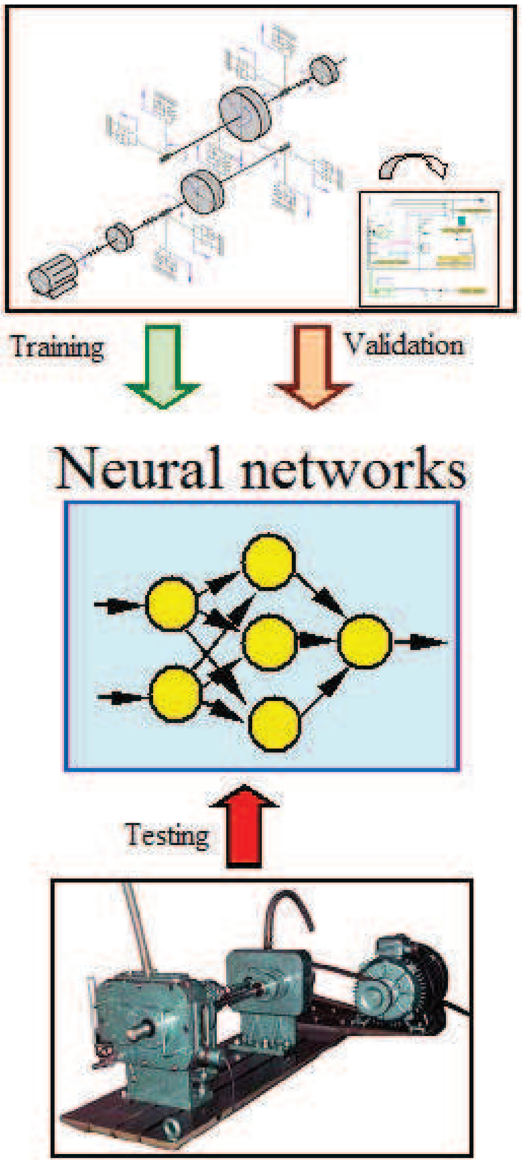

Fig. 6. Chart of the adopted methodology of working with neuron classifiers [1].

6. CONCLUSIONS

As results from the research presented in the paper, the methods applied to process the signal of transverse vibration speed of shafts, measured in the direction of the force acting between the teeth, and the use of analyses in, simultaneously, time and frequency or time and scale domains (CWT), facilitate effective detection of various faults of toothed wheels.

The achieved high qualitative and quantitative conformity of simulation and experimental research corroborates the fact that application of an expanded and identified dynamic model of a gearbox working in a power transmission system for simulating the faults of its components enables the acquisition of credible diagnostic relations.

The simultaneous application of experimental methods and computer simulations has facilitated the creation of input data to the system diagnosing local damage of wheels, working based on artificial intelligence methods. The research presented in the monograph [1] shows that artificial neuron networks, taught using data obtained from the model and from a real gearbox, offer the highest correctness of classification of the type and degree of fault in gears.

REFERENCES

[1] Czech P., Łazarz B., Wojnar G.: *Wykrywanie lokalnych uszkodzeń zębów kół przekładni z wykorzystaniem sztucznych sieci neuronowych i algorytmów genetycznych*. ITE Katowice - Radom 2007.

[2] Dąbrowski Z.: *Różne metody diagnozowania przekładni zębatych na podstawie pomiaru drgań i hałasu*. XXII Ogólnopolskie Sympozjum Diagnostyka Maszyn, Węgierska Górka marzec 1995 r., s. 35÷44.

[3] Dąbrowski Z., Radkowski S., Wilk A.: *Dynamika przekładni zębatych – Badania i symulacja w projektowaniu eksploatacyjnie zorientowanym*. Wydawnictwo i Zakład Poligrafii Instytutu Technologii Eksploatacji w Radomiu Warszawa – Katowice – Radom 2000.

[4] Lebold M., McClintic K., Campbell R., Byington C., Maynard K.: *Review of Vibration Analysis Methods for Gearbox Diagnostics and Prognostics*. 54th Meeting of Society for Machinery Failure Prevention Technology, Virginia Beach, VA, May 1-4, 2000, s. 623÷634.

[5] Łazarz B.: *Zidentyfikowany model dynamiczny przekładni zębatej w układzie napędowym jako podstawa projektowania*. Wydawnictwo i Zakład Poligrafii Instytutu Technologii Eksploatacji w Radomiu, Katowice-Radom 2001.

[6] Łazarz B., Madej H., Wilk A., Figlus T., Wojnar G.: *Diagnozowanie złożonych przypadków uszkodzeń przekładni zębatych*. ITE Katowice - Radom 2006.

[7] Łazarz B., Wojnar G.: *Detection of Early Stages of Pinion Tooth Chipping in Transmission Gear*. Machine Dynamics Problems 2003,vol. 27, No 3, s. 23÷34.

[8] Łazarz B., Wojnar G.: *Model dynamiczny układu napędowego z przekładnią zębatą*. XVII Ogólnopolska Konferencja Przekładnie Zębate, Węgierska Górka 09÷11.10.2000r., s. 101÷108.

[9] Łazarz B., Wojnar G., Czech P.: *Wibrometria laserowa i modelowanie – narzędzia*

współczesnej diagnostyki przekładni zębatych. ITE Katowice - Radom 2007.
[10] Madej H.: *Wykorzystanie sygnału resztkowego drgań w diagnostyce przekładni zębatych*. Diagnostyka, vol. 26, 2002, s. 46÷52.
[11] Müller L.: *Przekładnie zębate - dynamika*. WNT, Warszawa 1986.
[12] Stewart R. M.: *Some useful data analysis techniques for gearbox diagnostics*. Report MHM/R/10/77. Machine Health Monitoring Group. Institute of Sound and Vibration Research. University of Southampton 1977.
[13] Wilk A., Łazarz B., Madej H.: *Metody wczesnego wykrywania uszkodzeń w przekładniach zębatych*. Przegląd Mechaniczny, nr 3, 2002, s. 14÷18.
[14] Wilk A., Łazarz B., Madej H., Wojnar G.: *Analiza zmian wibroakustycznych symptomów diagnostycznych w procesach zużyciowych kół zębatych*. Materiały XXX Jubileuszowego Ogólnopolskiego Sympozjum Diagnostyka Maszyn, Węgierska Górka 03÷08.03.2003 r.

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