SPECTRUM WIDTH FACTOR AS A DIAGNOSTIC PARAMETER DETERMINING THE DEGREE OF DAMAGE OF TOOTH SURFACE

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Summary

The article discusses the issue of use of the spectrum width factor in diagnosing the development of pitting of toothed wheels. Theoretical issues have been presented related to the dependence of the level and structure of non-linear noise on the size, type and evolution phase of the process of degradation of surfaces of teeth being in contact. The paper discusses an example of diagnosis of the condition of teeth surfaces while using the data obtained during the experiment. An analysis of the relation between the spectrum width factor and the rigidity of shafts has also been conducted. The result of the analysis shows that the spectrum width factor can also be used in diagnosis of machine shafts.

Keywords: spectrum width factor, pitting, toothed gears.

WSPÓŁCZYNNIK SZEROKOŚCI WIDMA JAKO PARAMETR DIAGNOSTYCZNY STOPNIA USZKODZENIA POWIERZCHNI ZĘBÓW

Streszczenie

W artykule podjęto zagadnienie wykorzystania współczynnika szerokości widma w diagnozowaniu rozwoju pittingu kół zębatych. Przedstawiono zagadnienia teoretyczne odnośnie zależności poziomu i struktury zakłóceń nieliniowych od wielkości, rodzaju i fazy ewolucji procesu degradacji powierzchni zębów znajdujących się w przyporze. Omówiono przykład diagnozowania stanu powierzchni zębów z wykorzystaniem danych uzyskanych w trakcie eksperymentu. Przeprowadzono również analizę związku współczynnika szerokości widma ze sztywnością zastosowanych wałów. Wynik tej analizy wskazuje, że współczynnik szerokości widma może być wykorzystany również w diagnostyce wałów maszynowych.

Słowa kluczowe: współczynnik szerokości widma, pitting, przekładnie zębate.

1. INTRODUCTION – SPECTRUM WIDTH FACTOR

The publication [10] tackles the issue of origination and development of pitting in toothed wheels as well as monitoring of development of pitting with the use of spectrum width factor. The results presented therein show that the numerous factors can have influence on the intensity of the pitting process. While exploiting the possibilities offered by the test-bed, the influence of a toothed gear's operating conditions on the development of spectrum width factor has been examined.

Generally it is recognized [8, 3] that pitting is a process of wear due to fatigue which dominates in toothed gears with soft teeth which operate at average tangential velocity of below 50 m/s. A factor which leads to chipping is the variable contact stress which occurs in the area of negative slip. In addition, attention has been drawn to the fact [5, 9] that the physical and chemical properties of oil, thickness of the lubricating layer, hardness of the material and micro-geometry of surfaces will be the factors determining the intensity of the process of surface chipping. As a result of the surface wear process , pitting cavities emerge which, as the defect develops, form bigger strips of damaged surface whose width continuously increases. These strips most often occur in the area of a tooth's foot, in the area where the biggest slip occurs. This type of surface defects leads to reduction of the size of working surfaces and in the next stage of the destruction process they can become a place in which fatigue-related crack and the associated process of fatigue-related breaking of a tooth are initiated. Thus, diagnosis of emergence and development of pitting can play the role of detection of early defects during the phase of low-energy development of fatigue-related tooth breaking. Conducting of such a diagnosis means the need for developing the relevant methods of detecting diagnostic information which can be "coded" in various ways, depending on the phase of surface pitting process. The literature on the topic [7, 8] identifies three main phases of the process:

- the phase of initiation of cracks in the outer layer;

- the phase of development and propagation of cracks as a result of destructive operation of oil in the contact zones;
- the phase of development of pitting cavities, which results in removal of part of the material from the outer layer.

Description of the mechanism of emergence of fatigue-related cracks, while accounting for the fact that initiation of this process occurs in Bielayev's point, that is in the point where the stress on the material is the biggest, is presented in [5, 9].

Oil is forced into the cracks as the influence of friction forces increases in the contact zone and Bielayev's point is moved in the direction of the friction surface, which is a signal confirming the start of the second phase of the destruction process. Rolling of the elements mating in such conditions leads to variable impact on the extensive network of cracks and in the third stage it leads to chipping of further particles from the elements (profiles). Such destruction constitutes substantial disturbance of contact conditions and hence it can become a reason for changes of the frequency structure of the generated vibroacoustic signal. Generally, as pointed out in [4, 6], overall growth of the noise level, in a broad frequency band of the analyzed signal, will occur in the case of development of pitting.

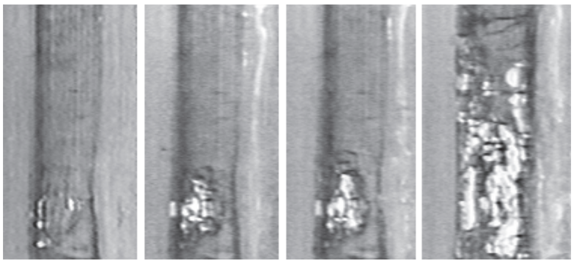


Fig. 1. Development of pitting on a tooth surface (from an experiment)

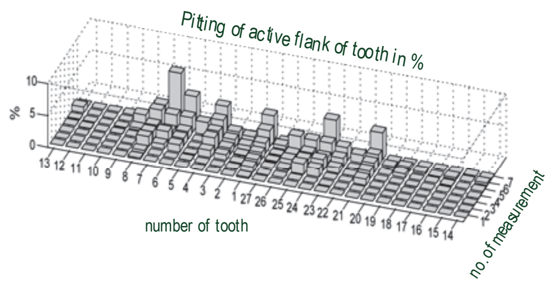


Fig. 2. Development of pitting in respective teeth of the pinion.

The method of modeling of vibroacoustic signal generation, including the impact of various methods of causing damage on a vibroacoustic signal's parameters and hence leading to change of parameters of a dynamic model, is discussed in detail in [10]. Pitting in toothed wheels was examined and the results are presented below. Fig. 1 presents an example of growth of bandwidth in the case of a surface which was chipped due to wear. In addition, during the surveys we noted that pitting could start on one or bigger number of teeth and then spread to the remaining teeth (Fig. 2).

Use of spectrum width factor has been proposed for modeling of pitting in toothed wheels. The method of calculating the spectrum width factor is presented below. Spectral moments have to be determined for this purpose according to the following formula [1]:

$$m_k = \int_{-\infty}^{\infty} \omega^k S(\omega) d\omega \tag{1}$$

and then the measure of spectrum width has to be determined in the form of spectrum width factor:

$$\nu = \frac{m_2^2}{m_0 m_4} \tag{2}$$

where:

$$m_0 = \int_{-\infty}^{\infty} S(\omega) d\omega$$

$$m_2 = \int_{-\infty}^{\infty} \omega^2 S(\omega) d\omega$$

$$m_4 = \int_{-\infty}^{\infty} \omega^4 S(\omega) d\omega$$

$S(\omega)$ - spectrum,

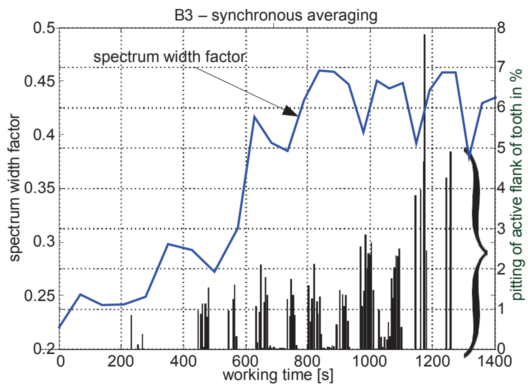


Fig. 3. Changes of the value of spectrum width factor during the time of the strength test.

Fig. 3 presents the changes of the value of the spectrum width factor in time during the strength test. In accordance with the results found in Fig. 2, as the test continues we witness increase of the number of teeth affected by the fatigue-related process of surface destruction. The aforementioned fact has been reflected accordingly by the changing width of the bar on the abscissa. The heights of respective bars correspond to the percentage of destructed surface of a tooth's side as compared to the total surface. Let us note, that it is reflected by the changes of spectrum width factor, however in addition one can note the quality change associated with damage to surfaces of further teeth. Let us note that the qualitative change is observed already in the case of destruction of only several percent of a tooth's surface. Thus a diagnostic parameter has been obtained which is highly sensitive, especially during the initial phase of pitting.

2. DESCRIPTION OF THE EXPERIMENT

The experiment was conducted in revolving power test-bed. The test-bed consists of two toothed gears which operate in revolving power system and it enables examination of both, toothed wheels and toothed gear lubricants. The precise description of the test-bed is found in [2]. Toothed wheels made of 20H2N4A steel, carburized and hardened to hardness of 60 HRC were used in the experiment. They were subjected to accelerated fatigue testing.

The experiment was planned in such a way so as to enable analysis of the impact of various factors on the degradation process (load and gear quality).

In addition two sets of shafts were used with different torsional rigidity, which enabled examination of the impact of torsional rigidity on the conditions of mating of teeth coming into contact.

Parameters of examined toothed wheels are found in Table 1.

Table 1 Comparison of parameters of examined toothed wheels

No. of experi-ment	Torsional rigidity of shafts	Experiment time [s]	Input rotational speed [rev/s]	Load [Nm]
1	Two times bigger as in case of second shafts ($K_{T1}=2K_{T2}$)	10254	24	1222
2		3960		1303
3		1188		1492
4		5922		1200
5	Smaller (K_{T2})	7770		1218
6		8238		1214
7		4206		1309
8		6186		1294

The measurement system mounted in the test-bed enabled registration of five different signals:

- channel 1 – revolutions marker (one marker per revolution)
- channel 2 – signal from tensometers affixed to the shaft, proportional to the degree at which a shaft is twisted
- channel 3 – signal from tensometers affixed at the of a tooth's head, proportional to tooth deflection
- channels 4 and 5 – acceleration of vibration in the body of the examined toothed gear as measured at the body's upper part, just above the place of mounting of pinion shaft bearing, in a horizontal direction – perpendicularly to shaft axis, and in vertical direction.

Channels 2 and 3 were equipped with a telemetric system manufactured by ESA Messtechnik GmbH. The system enabled data transmission from rotating elements. Tensometers manufactured by MEASUREMENTS GROUP INC. served as the active measuring elements. The information obtained this way was used for tracking the deformations at the foot of a tooth as well as the shaft torsion angle during the experiment. The information obtained this way was used for determining the moment of crack initiation and for tracking of a crack's propagation. An inductive sensor was also installed in the examined toothed gear. It shut down the test bed at the moment when a tooth broke.

The experiments were conducted until total breaking of a tooth while at the same time conducting continuous registration (in 6-second-long modules). It is worth stressing that no artificial defects were introduced prior to starting the tests, so as not to disturb this way the course of the process of initiation of a fatigue-related breaking of a tooth. Such a method of research differs substantially from the research related to examining the development of a tooth's breaking in which artificial defects are introduced, e.g. by cutting the tooth. The adopted method of realization of the experiments resulted in a situation that in most cases the teeth which broke were not the ones for which stress measurements were carried out.

Based on the vibration signals registered in two directions, we were able to determine the diagnostic parameters in the form of width factor of power spectrum for a broadband signal of vibration acceleration as well as of signals generated by acceleration of vibration filtered off in the bands with widths of 120Hz, 400Hz, 600Hz surrounding the first eight harmonic frequencies of meshing.

Due to the fact that the time till occurrence of a defect varied for respective toothed wheels, thus to facilitate the analysis of results the time was standardized and presented in the form of percentage of time till defect occurrence.

3. MONITORING OF PITTING DEVELOPMENT

Due to the fact that during the fatigue tests there also occurred pitting-related damage of teeth's surfaces, thus it is worth analyzing the change of spectrum width factor for such a wheel and confirm its utility value in the process of monitoring of pitting development. Changes of spectrum width factors were analyzed for the wheel in which seven teeth suffered from pitting. The information on the development of pitting is found in the signal's spectrum, in direction X (horizontal-and-perpendicular to shaft axis) and it is presented in the form of a spectrum width factor for the entire frequency band (Fig. 4).

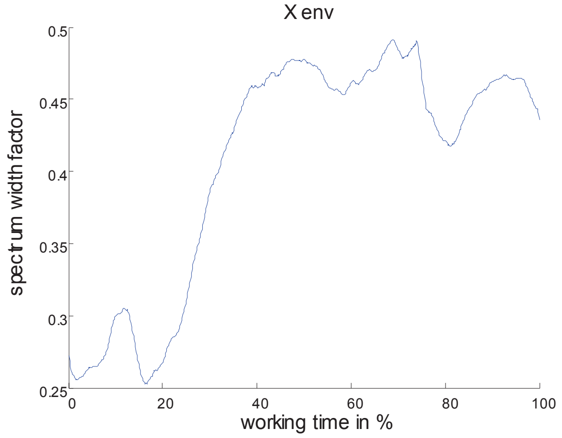


Fig. 4. Spectrum width factor of a signal's vibration acceleration in direction X

During the initial period of the test the value of spectrum width factor demonstrated no upward trend, while a distinct upward trend became visible after 20% of the test's time. This could have been associated with the phase of initiation of pitting-related defects. After some time the trend was halted, which most probably meant end of the phase of intensive development of pitting.

An interesting task is posed by determination of the frequency band in which the information on development of pitting can be found. To this end the spectrum width factor has been determined in frequency bands with the width of 120Hz around subsequent harmonics of meshing (the first eight). A similar qualitative change growth of spectrum width factor, as in the case of the whole frequency band of the analyzed signal, could be observed in the bandwidth surrounding the third harmonic of meshing, the scale of qualitative change in this case is quite different (Fig. 5).

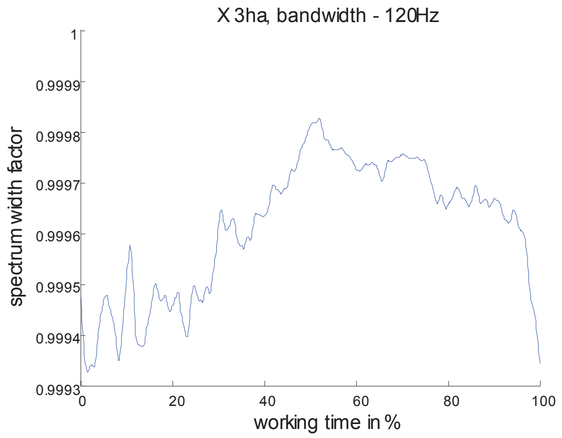


Fig. 5. Spectrum width factor of signal vibration acceleration in direction X in the bandwidth surrounding the third meshing harmonic.

Spectrum width factor, for the signal registered in direction Z (in the entire frequency band) whose run is presented in Fig. 6, also maintained an upward trend, however the level of random noise is substantially higher than in direction X.

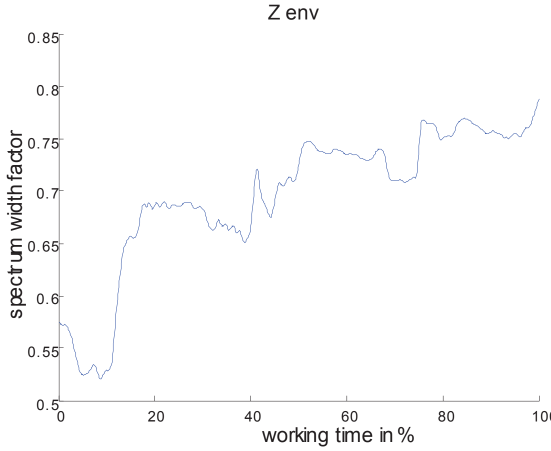


Fig. 6. Spectrum width factor of signal vibration acceleration in direction Z

In this case it is difficult to indicate the bandwidth which is characterized by particular sensitivity to the process of pitting development. The bandwidth around the 6th harmonic frequency can be considered to be the one which reflects the general trend in the biggest degree (Fig. 7).

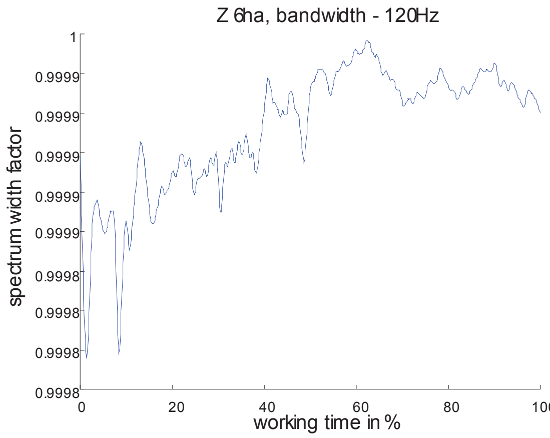


Fig. 7. Spectrum width factor of signal vibration acceleration in direction Z in the bandwidth surrounding the sixth harmonic frequency.

We also conducted the analyses in the bands with widths of 400Hz and 600Hz – the obtained results did not differ significantly. This indicates that the information on the occurrence and development of pitting is encoded in a narrow band around relevant harmonic frequencies which correspond to occurrence of amplitude modulation.

4. ANALYSIS OF THE IMPACT OF TORSIONAL RIGIDITY

The possibility of using the prepared characteristics was analyzed in order to be able to distinguish the values of individual parameters of the experiment. The results concerning the torsional rigidity of shafts are presented below. The grey color denotes the runs determined on the basis of registered signals in a situation when shafts with higher rigidity were mounted, while the black color denotes the runs associated with shafts having smaller rigidity).

It turned out that the most useful diagnostic parameters in this task were the spectrum width factors for the following signals:

- in direction X in the bandwidth around:
  - the first harmonic frequency of meshing with bandwidth of 400Hz (Fig. 8);
  - the fifth harmonic frequency of meshing with bandwidth of 120Hz, 400Hz, 600Hz (Fig. 9);
- in direction Z in the bandwidth around:
  - the fifth harmonic frequency of meshing with bandwidth of 120Hz (Fig. 10);

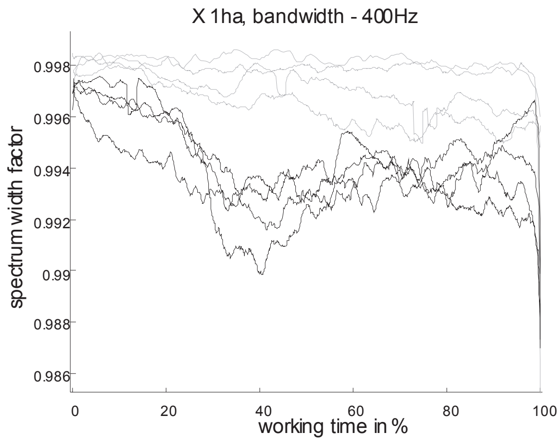
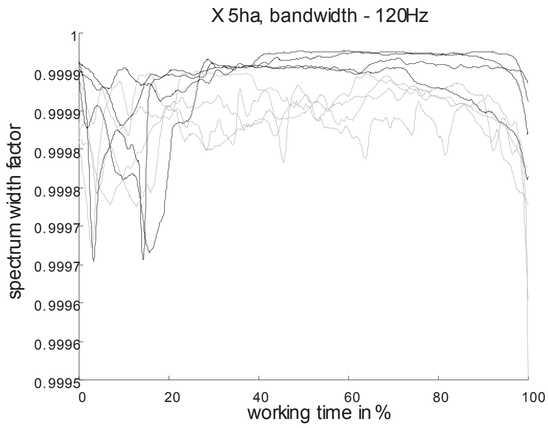
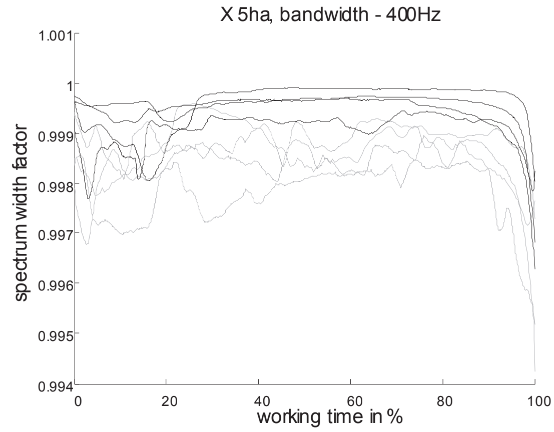


Fig. 8. Spectrum width factor of signal vibration acceleration in direction X in the bandwidth surrounding the first harmonic frequency with width of 400Hz.

a)



b)



c)

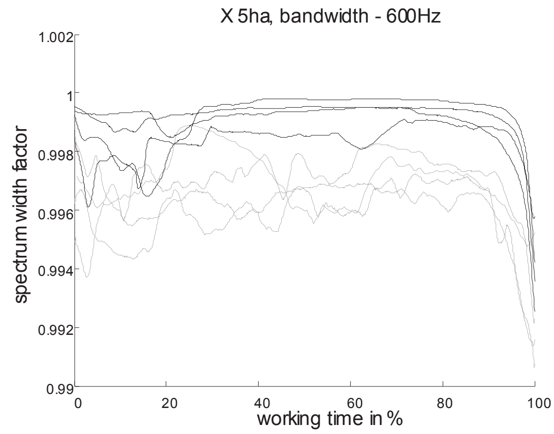


Fig. 9. Spectrum width factor of signal vibration acceleration in direction X in the bandwidth surrounding the fifth harmonic frequency with widths of: a) 120Hz, b) 400Hz, c) 600Hz

The above presented diagnostic parameters enable diagnosis of rigidity of the shafts which were used. Attention should be drawn to the fact that information on rigidity of shafts is hidden in various frequency ranges, however the bandwidth surrounding the fifth harmonic frequency of meshing, with width of 600 Hz in direction X, seems to have the biggest information value. The above presented property results in a situation that the spectrum width factor, determined in relevant bands, can be used for detecting shaft defects (the defects which lead to changes of its rigidity). The relation between effectiveness of separation and bandwidth points to big influence of torsional rigidity of shafts in toothed gears on tooth contact conditions, and in the case of wheels with spur wheel - on the conditions of mating along the contact line. At the same time, the above means that the phenomenon of frequency modulation is the most appropriate model for the purpose of qualitative and then quantitative description of the influence of the shafts' torsional rigidity on contact conditions. The results of analysis of various widths of the examined spectrum surrounding the same carrier frequency, as presented in Fig. 9, enable such a conclusion to be formulated.

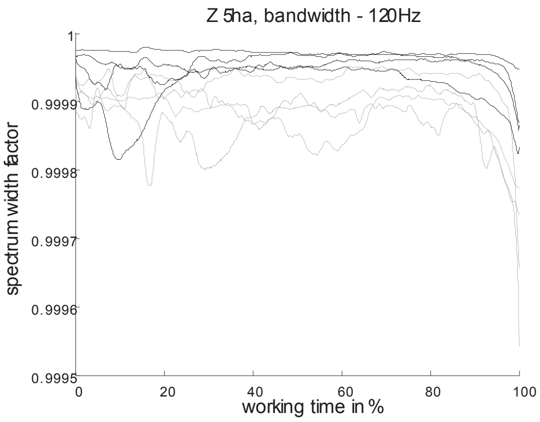


Fig. 10. Spectrum width factor of signal vibration acceleration in direction Z in the bandwidth surrounding the first harmonic frequency with width of 120Hz

5. CONCLUSIONS

The conducted research demonstrates usefulness of spectrum width factor in diagnosis of pitting in toothed wheels. In addition, the parameter is sensitive to the rigidity of the shafts used, thanks to which it can be used for diagnosing these elements. It is particularly interesting to examine the sensitivity of spectrum width factor to other system variables in the context of the factor's sensitivity to change of shafts' rigidity. This means an attempt of obtaining the answer to the following question: Will the change of the shafts' torsional rigidity, caused by defect, lead in addition to any qualitative change in the phenomenon-oriented measures which register disturbance of conditions of mating of specific kinematic nodes of the monitored system, other than changes in the structure of harmonic frequencies of meshing?

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6. BIBLIOGRAPHY

[1] Cempel Cz., (1982) *Podstawy wibroakustycznej diagnostyki maszyn*, WNT, Warszawa;
[2] Dybała J., Mączak J., Radkowski S., (2006): *Wykorzystanie sygnału wibroakustycznego w analizie ryzyka technicznego (Use of vibroacoustic signals in technical risk analysis*), ITE Warszawa – Radom 2006;
[3] Dziama A., Michniewicz M., Niedźwiedzki A.: (1995) *Przekładnie zębate (Toothed gears*), PWN Warszawa.
[4] Gienkin M. D., Sokołowa A. G.: (1987) *Wibroakusticzeskaja diagnostika maszin i mechanizmów, Maszinostrojenije*, Moskwa.
[5] Lawrowski Z.: (1993) *Tribologia – tarcie i smarowanie (Tribology – friction and lubrication),* W.N. PWN Warszawa.
[6] Muschaweck F.: (1988), *Untersuchengen zur Klassifikation von Fehler- und Schadenbedingten Betriebzuständen an einstufigen Stirnradgetrieben,* rozpr. dok., RWTH Achen.
[7] Nadolny K.: (1998) *Tribologia kół zębatych, Zagadnienie trwałości i niezawodności (Tribology of toothed wheels. Durability and reliability*), ITE Radom.
[8] Niemann G., Winter H.: (1983) *Machinenelemente Band II. Getriebe allgemein, Zahnradgetriebe – Grundlagen*, Stirnradgetriebe, Springer-Verlag, Berlin.
[9] Pytko S., Szczerek M.: (1993*) Pitting – forma niszczenia elementów tocznych (Pitting – a form of wear of rolling elements*), Tribologia no. 4/5.
[10] Radkowski S.: (2002) *Wibroakustyczna diagnostyka uszkodzeń niskoenergetycznych (Vibroacoustic diagnosis of low-energy defects*), Instytut Technologii Eksploatacji, Warszawa-Radom.

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