COMPARISON OF THE EFFICIENCY OF SELECTED VIBRATION MEASURES USED IN THE DIAGNOSIS OF COMPLEX CASES OF TOOTH GEAR DAMAGE

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Summary

The diagnostics of tooth gears is a vital scientific issue for its utilitarian and cognitive aspects. An essential part of this process is the ability to differentiate the impact of various effects on the vibration signal of a tooth gear both working in the correct mode, including meshing of the tooth gear, and possible damage to it.

The papers of authors present various diagnostic measures applied in the detection of tooth gear damage. They are based on specially processed and filtered vibration signals. This paper presents an attempt to compare the sensitivity of selected diagnostic measures to the studied types of tooth gear damage in the work of tooth gears with bearings of various technical conditions.

Keywords: diagnostics, tooth gear damage, complex cases, efficiency of measures.

PORÓWNANIE SKUTECZNOŚCI WYBRANYCH MIAR DRGANIOWYCH STOSOWANYCH W DIAGNOZOWANIU ZŁOŻONYCH PRZYPADKÓW USZKODZEŃ PRZEKŁADNI

Streszczenie

Ze względów utylitarnych i poznawczych diagnozowanie przekładni zębatych jest ważnym zagadnieniem naukowym. W procesie tym istotna jest umiejętność rozróżnienia oddziaływania na sygnał drganiowy przekładni różnych zjawisk związanych zarówno z normalną pracą przekładni, a w tym zazębianiem się kół, jak i uszkodzeniami, które mogą w niej wystąpić.

W publikacjach autorów do wykrywania uszkodzeń przekładni zębatych przedstawione są różne miary diagnostyczne. Bazują one na odpowiednio przetworzonych i filtrowanych sygnałach drganiowych. W niniejszej pracy przedstawiono próbę porównania wrażliwości niektórych miar diagnostycznych na badane rodzaje uszkodzeń kół zębatych w przypadku pracy przekładni z łożyskami w różnym stanie technicznym.

Słowa kluczowe: diagnostyka, uszkodzenia kół zębatych, wrażliwość miar.

1. INTRODUCTION

The diagnostics of tooth gears is a vital scientific issue for its utilitarian and cognitive aspects. An essential part of this process is the ability to differentiate the impact of various effects on the vibration signal of a tooth gear both working in the correct mode, including meshing of the tooth gear, and possible damage to it.

The methods described in literature concerning the detection of tooth gear damage have been developed providing that the damages do not coincide. The precise specification of gear tooth condition is considerably hindered when damage to other elements of the tooth gear, e.g. bearings, occurs simultaneously. In such cases the vibration signal generated by the tooth gear contains additional modulations resulting from the concurrent damage of tooth gears and bearings.

The papers of different authors present various diagnostic measures applied in the detection of tooth gear damage. They are based on e.g. Wigner-Ville distribution, continuous wavelet analysis, and the envelope spectrum of appropriately processed and filtered vibration signals. This paper presents an attempt to compare the sensitivity of selected diagnostic measures on the studied types of tooth gear damage in the work of tooth gears with bearings in various technical conditions.

2. EXPERIMENTAL STUDIES

The experimental studies applied a unit working in a power circulating system. During the studies the tooth gear worked as a reducer. The acceleration and vibration velocity for selected locations of the tooth gear casing, and the vibration velocity of its transverse shafts were measured. Apart from that, synchronic reference signals corresponding to the shaft rotations were recorded [3, 17].

The experimental studies concerned wheels with two different hardness factors, depending on the performed experiment:

- 60-62 HRC (carbon coated) – diagnostics of tooth top crushing and tooth base cracking, - 37-40 HRC (carbon coated and tempered) – diagnostics of wear of tooth working surface.

While modelling the tooth crushing at subsequent stages of an active experiment, the height of the head of one wheel tooth was lowered by grinding off the appropriate quantity of material: 0.75, 1.5 and 2.0 mm. This operation resulted in the shortening of the contact line of the tooth and a decrease in the local contact ratio *CR* (Table 1).

Table 1. Influence of lowered height of the head of a wheel tooth on local contact ratio

Lowered height of the head of tooth head [mm]	Local contact ratio *CR* [-]
0	1.32
0.75	1.18
1.5	1.03
2.0	0.93

Measurements of tooth gear vibration aimed at the specification of the influence of the wear of the tooth’s working surface on the diagnostic signal were performed in four phases which corresponded with the different phases of the wear of the tooth’s surface (Fig. 1).

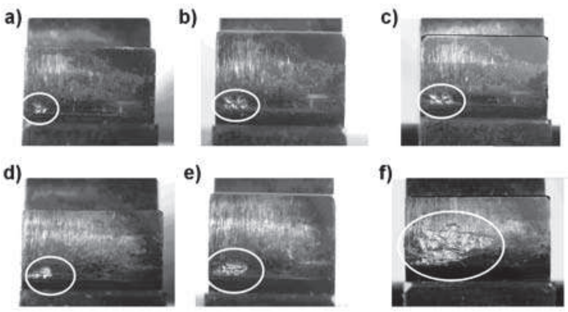


Fig. 1. Subsequent phases of the wear of the tooth’s working surface: a) - c) tooth 1, d) - f) tooth 2

The shafts of the power circulating unit were supported by ordinary ball bearings. The experimental study applied bearings in good technical condition, with modelled damage of bearing raceway, and raceway worn out in long-term use (Fig. 2).

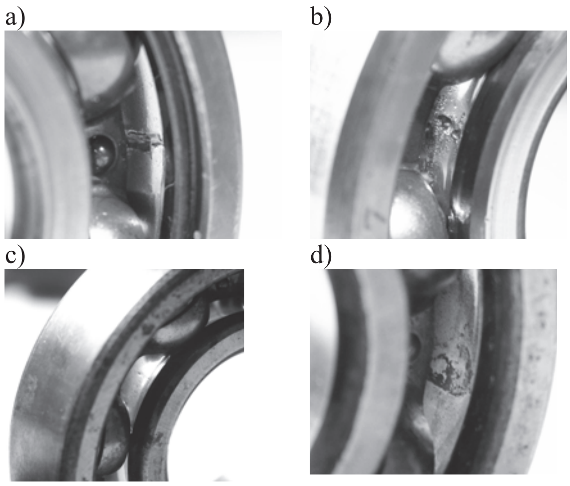


Fig. 2. Damage (wear) of ball bearing raceways: a) damage to outer raceway; b) damage to inner raceway; c)-d) usual wear

3. SIMULATION STUDY

One of the most common types of damage to tooth gears is cracking at the base. An initial study carried out by the authors of this paper demonstrated that fast tooth cracking progress [18, 13, 14, 8, 10, 17, 3] disables the possibility of the recording and comparison of the same phase of cracking in the case of bearing shafts with different experimentally established degrees of damage. For that reason it was necessary to carry out simulation studies and their experimental verification by the performance of several short series of studies on a working unit. For the simulation of the tooth base cracking this study employed a dynamic model of a tooth gear in a drive unit developed at the Faculty of Transport of the Silesian University of Technology and performed in the Matlab-Simulink environment [5, 4]. The application of this model in the diagnostics of local damage, dynamic analysis or designing requires the identification of the parameters of this model. Within the framework of the study [4] the identification of the friction factor in meshing was carried out and the values of the meshing attenuation factor were specified by the comparison of the values of effective accelerations of the torsional vibration of the wheel, which were measured and obtained by simulation. One of the significant factors determining the compliance of obtained results with the experiment was the identification of attenuation for bearing nodes [6, 17].

4. SIGNAL FILTERING

The separation of components containing information on wheel damage is possible, in accordance with papers [12, 9, 8, 17, 3], by residual filtering, also named differentiation filtering [8, 9, 17, 3].

The diagnosis of tooth gear condition is considerably hindered in the case of concurrent damage in its other element, e.g. a bearing. In such a case the vibration signal of the tooth gear contains an additional component resulting from bearing damage. Therefore, it is suggested that direct comb filtering for diagnostic purposes is used. To identify the damage to tooth gears by this method filters are used which transmit frequency bands connected with a wide-bandwidth signal modulation $k \cdot f_u$, where: f_u – rotational frequency of a damaged wheel, and $k \in C^+$. Two options for the performance of the direct comb filter were assumed: the first option provides that information concerning tooth gear damage is only contained in harmonic bands of rotational frequency of a pinion (filter I) or a wheel (filter II), and in the second option information concerning damage is contained in harmonic bands of rotational frequency of the pinion and wheel (filter III). Based on such prepared signals the diagnostic measures demonstrated in part 5 were determined.

5. DIAGNOSTIC MEASURES

Measure M_{wWV} (2) was proposed for the diagnosis of local wheel damage, and was determined based on the signal obtained as a result of the summation of the discrete values of the Wigner-Ville distribution [7] denominated *SWWV* (1).

$$SWWV(i) = \sum_{j=1}^{K} WV(i,j) \qquad (1)$$

where:
WV(i,j) – discrete values of Wigner-Ville distribution,
i = 1, 2, ..., N,
N – number of line of *WV(i,j)* distribution corresponding with a 360° turn of a wheel,
K – number of column of *WV(i,j)* distribution corresponding with the top frequency limit

$$M_{wWV} = \frac{SWWV_{UMAX} - \overline{SWWV}}{\overline{SWWV_b}} \qquad (2)$$

where:
$SWWV_{UMAX}$ – maximum value of *SWWV*,
$\overline{SWWV}$ – mean value of *SWWV*,
$\overline{SWWV}_b$ – mean value of baseline signal *SWWV*(*i*) determined in the case of meshing and bearing mounting in good conditions.

Measure M_{wCWT} (4), similar to M_{wWV} (2), was used to diagnose local wheel damage. It is determined based on the signal obtained as a result of the summation of the discrete values of continuous wavelet transform [2] denominated *SWCWT* (3).

$$SWCWT(i) = \sum_{j=A_{CWT}}^{B_{CWT}} C_{ab}(j,i), \qquad (3)$$

where:
$C_{ab}(j,i)$– discrete values of continuous wavelet transform *CWT*,
i = 1, 2, ..., N,
N – number of column of $C_{ab}(j,i)$ distribution corresponding with a 360° turn of a wheel,
A_{CWT} – number of line of $C_{ab}(j,i)$ distribution corresponding with the bottom limit of scale range (frequency),
B_{CWT} – number of line of *Cab(j,i)* distribution corresponding with the top limit of scale range (frequency),

$$M_{wCWT} = \frac{SWCWT_{UMAX} - \overline{SWCWT}}{\overline{SWCWT_b}} \qquad (4)$$

where:
$SWCWT_{UMAX}$ – maximum value of *SWCWT*,
$\overline{SWCWT}$ – mean value of *SWCWT*,
$SWCWT_b$ - mean value of baseline signal *SWCWT(i)* determined in the case of meshing and bearing mounting in good condition.

Vibroacoustic diagnostics often applies an envelope spectrum, whose utility in the diagnosis of wheel meshing was demonstrated in papers [1, 15, 11]. To define changes in the envelope spectrum the *SWWO* measure defined by the correlation (9.5) was proposed:

$$SWWO = \sum_{i=1}^{K} \left| X(f_i) \right| , \qquad (5)$$

where:
$X(f_i)$ –amplitude of *i*-th component of envelope spectrum,
fi – frequency of *i*-th component of spectrum,
i – number of spectrum component,
K – number of discrete spectrum components.

To diagnose local damage in a tooth gear a discrete wavelet transform [2] was also used with the incorporation of the Daubechies 2 wavelet.

Owing to the specific nature of signal changes caused by the tooth base cracking further calculations applied the measure M_{wDWT}, determined according to the correlations (6, 7), based on the signal reconstructed at the subsequent stages of decomposition. Apart from that, the summarized measure SD1-5, i.e. the sum of the values of M_{wDWT} measures for details 1 to 5, was applied.

$$M_{wDWT(Di)} = \frac{D_{iUMAX} - \overline{D_i}}{\overline{D_{ib}}} \qquad (6)$$

or

$$M_{wDWT(Ai)} = \frac{A_{iUMAX} - \overline{A_i}}{\overline{A_{ib}}}, \qquad (7)$$

where:

D_{iUMAX}, A_{iUMAX} – maximum value of a detail or approximation,

$\overline{D_i}$, $\overline{A_i}$ – mean value of a detail or approximation,

$\overline{D_{ib}}$, $\overline{A_{ib}}$ - baseline mean value of a detail or approximation calculated for meshing and bearing mounting in good condition,

i – number of a detail or approximation.

As in paper [16] the measure of the wear of tooth surface was determined as the sum of the discrete values of the Wigner-Ville distribution:

$$SWV = \sum_{i=1}^{N} \sum_{j=1}^{K} WV(i,j), \qquad (8)$$

where:

WV(i,j) – discrete values of Wigner-Ville distribution,

N – number of line of *WV(i,j)* distribution corresponding with a 360° turn of a wheel,

K – number of column of *WV(i,j)* distribution corresponding with the top frequency limit.

The measure describing the wear of tooth working surface calculated based on continuous wavelet transform applied the *SCWT* parameter calculated from the correlation (9):

$$SCWT = \sum_{i=1}^{N} \sum_{j=A_{CWT}}^{B_{CWT}} C_{ab}(j,i) \qquad (9)$$

where:

Cab(j,i) – discrete values of continuous wavelet transform *CWT*,

N – number of column of *Cab(j,i)* distribution corresponding with a 360° turn of a wheel,

A_{CWT} – number of line of *Cab(j,i)* distribution corresponding with the bottom limit of scale range (frequency),

B_{CWT} – number of line of *Cab(j,i)* distribution corresponding with the top limit of scale range (frequency).

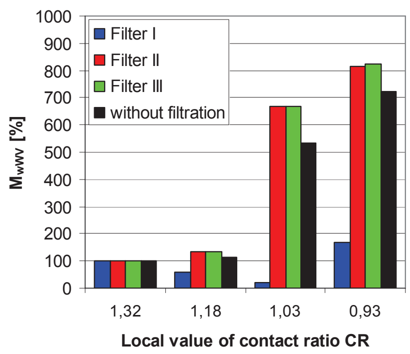
Discrete wavelet analysis was also used to identify the wear of tooth working surface. As in the detection of tooth gear crushing, the stages of signal decomposition were identified, for which the largest energetic changes were observed. Based on initial studies the coif 1 wavelet was selected and the condition imposed that the analysis of the signal should be performed at 5 stages of decomposition. For the analysis of vibration signal, including signals obtained from details and approximation, the calculation of root-mean-square (*RMS*) and central moment of 4th degree (M4) was proposed.

More information concerning the presented measures is contained in [7].

6. ESTIMATION OF MEASURES EFFICIENCY

This section presents a comparison of the sensitivity of the studied diagnostic measures to the studied types of tooth gear damage in the work of a tooth gear with bearings in various technical conditions. However, this will be introduced by the sensitivity of the M_{wWV} measure to the changes of the value of the local contact ratio for various types of direct comb filtering in the case of the work of a tooth gear with good bearings (Fig. 3). The demonstrated results of the analysis indicate that within the harmonic rotational frequencies of a pinion and gear only the harmonics of the wheel with a damaged tooth contain information on crushing presence.

a)



b)

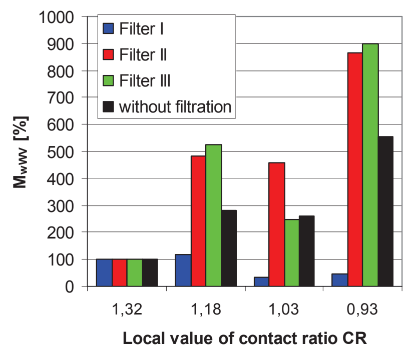
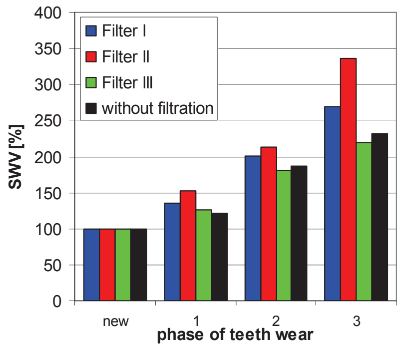


Fig. 3. Percentage value of M_{wWV} depending on the type of direct comb filtering and local contact ratio:
a) measurements of shaft vibrations,
b) measurements of casing vibrations

In the case of tooth top crushing resulting in the decrease of local contact ratio to 1.18, the increase of M_{wWV} measure expressed in percent was greater when the measure was calculated based on the signal of accelerated vibrations of the tooth gear casing (Fig. 3b) than when it was based on the shaft vibration velocity signal (Fig. 3a). However, a continued increase of the simulated tooth crushing, resulting in the decrease of the local contact ratio to 1.03, no longer resulted in the increase of the M_{wWV} measure (even decreasing it) when it was calculated based on the signal of accelerated vibrations of the tooth gear casing (Fig. 3b). This increase occurred, however, when the measure in question was calculated based on the shaft vibration velocity (Fig. 3a), both in the case of used filter II and filter III.

Figure 4 demonstrates the changes in *SWV* value depending on the type of direct comb filtering and the phase of wear of tooth working surface. As in the already discussed part, the results refer to the work of a tooth gear with efficient bearings. It can be stated based on the obtained results that the application of direct comb filtering does not deteriorate the sensitivity of measures considerably, and in the diagnostics of a tooth gear with damaged bearings enables the inclusion in the analysis of only the signal components containing information on tooth gear damage. This enables us to ignore highly energetic signal components connected with bearing damage and the diagnostics of the tooth gear in the case of concurrent bearing damage.

a)



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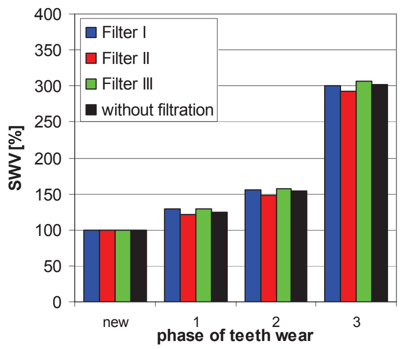


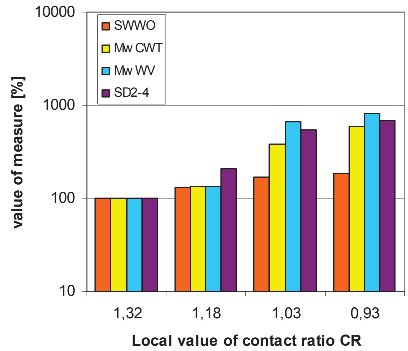
Fig. 4. Percentage *SWV* value depending on the type of direct comb filtering and the phase of wear of tooth working surface: a) measurements of shaft vibrations, b) measurements of casing vibrations

In the first and second phases of the wear of the tooth working surface the *SWV* measure, calculated based on the signal of shaft vibration velocity, increases more considerably than for *SWV* calculated based on the signal of accelerated vibrations of the tooth gear casing (Fig. 4).

The results demonstrated in Figures 3 and 4 suggest that an appropriate direct comb filtering, especially with respect to tooth gear shaft vibrations, results in a greater increase in damage and wear measures than in the case of their calculation based on non-filtered signals. Additionally, as previously mentioned, it enables us in most cases to ignore the frequencies connected with ball bearing damage.

While comparing the sensitivity of measures (Fig. 5, 6) on tooth top crushing in the work of a tooth gear with bearings in various technical conditions it can be stated that the highest increase expressed in percent is typical for measures based on the Wigner-Ville distribution and wavelet transform.

a)



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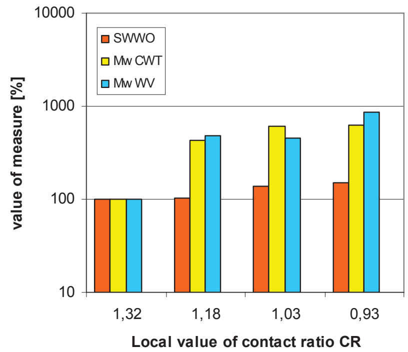

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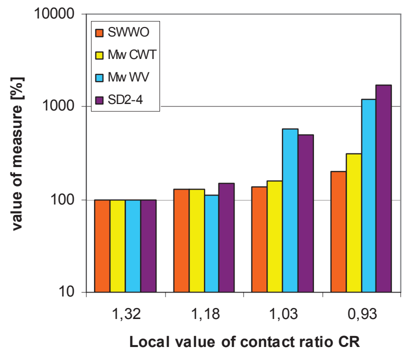
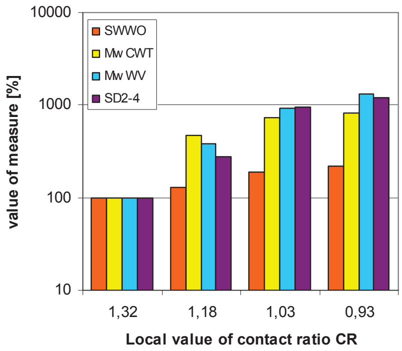


Fig. 5. Change in percent value of selected measures depending on the value of local contact ratio – tooth gear load Q=3.85MPa: a) good bearings - measurements of shaft vibrations, b) good bearings – measurements of casing vibrations, c) damage to inner raceway - measurements of shaft vibrations

a)



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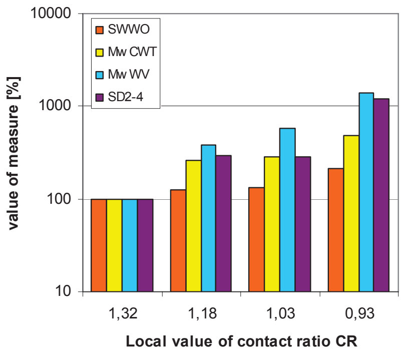

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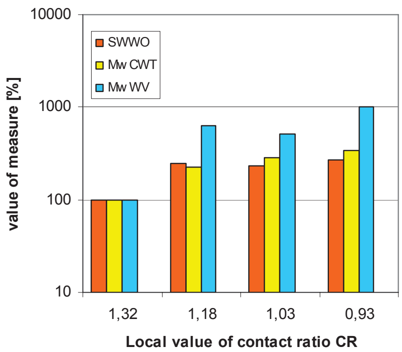
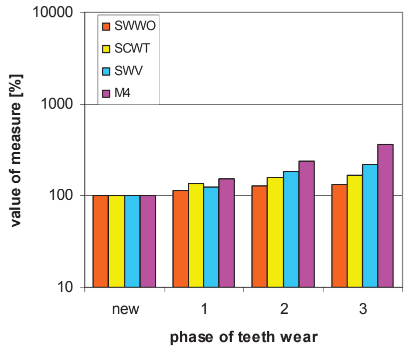


Fig. 6. Change in percent value of selected measures depending on the value of local contact ratio – tooth gear load Q=3.85MPa: a) damage to outer raceway - measurements of casing vibrations, b) damage to inner raceway - measurements of shaft vibrations c) damage to inner raceway - measurements of casing vibrations

The measure based on the central moment of the fourth degree proved to be very sensitive for the wear of the tooth working surface, the same as for the measure based on the Wigner-Ville distribution. The values of the measures presented in Figures 7 and 8 were calculated based on appropriately filtered vibration signals (filter III).

a)



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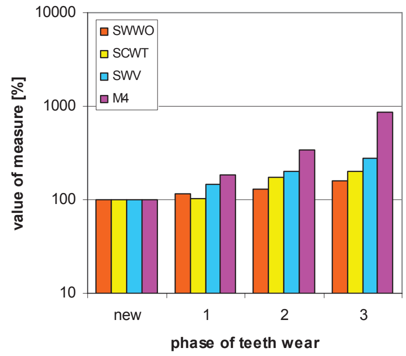

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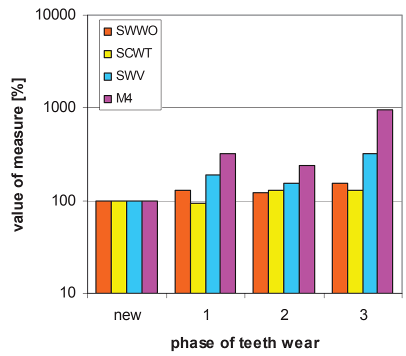

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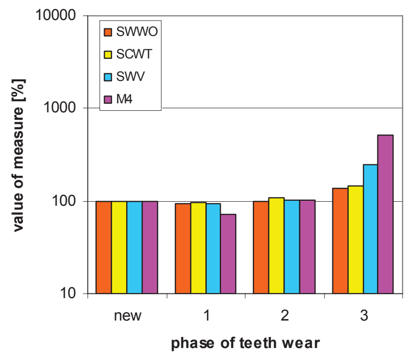

Fig. 7. Change in percent value of selected measures depending on the phase of tooth wear – shaft vibration measurement at tooth gear load Q=3.1MPa: a) good bearings, b) damage to outer raceway, c) damage to inner raceway, d) usual wear of bearings

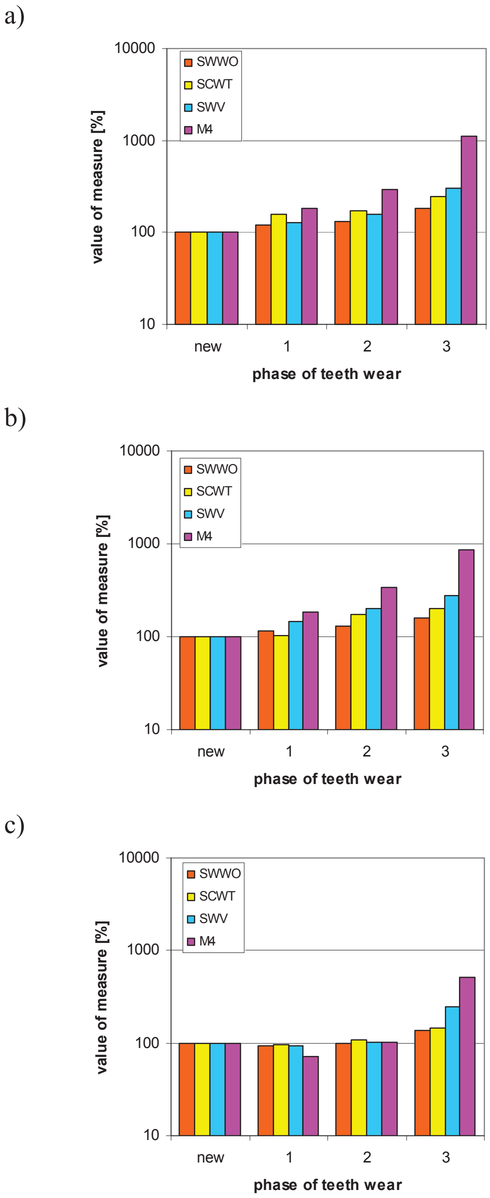

Fig. 8. Change in percent value of selected measures depending on the phase of tooth wear – casing vibration measurement at tooth gear load Q=3.1MPa: a) good bearings, b) damage to outer raceway, c) usual wear of bearings

In tooth base cracking, as in tooth top crushing, the suggested measures calculated based on appropriately filtered vibration signals are sensitive to this local damage (Fig. 9).

7. CONCLUSIONS

The results enable us to state that the application of direct comb filtering does not deteriorate the sensitivity of measures considerably. In the diagnostics of tooth gears with damaged bearings it is advisable to include in the analysis only those signal components containing information on tooth gear damage. This enables us to ignore highly energetic signal components connected with bearing damage and to diagnose the tooth gear in the case of concurrent bearing damage.

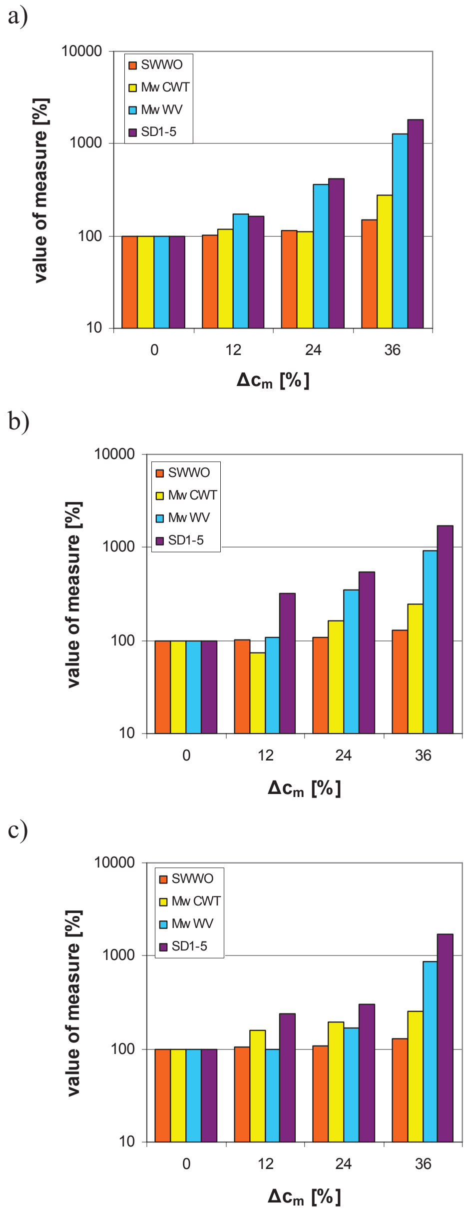

Fig. 9. Change in percent value of selected measures depending on the decrease in the achieved meshing rigidity Δc_m resulting from the cracking of the wheel tooth and the decrease in rigidity in the bearing nod resulting from damage to: a) outer bearing raceway equal to 10% ($\Delta f/f$=0.1), b) outer bearing raceway equal to 20% ($\Delta f/f$=0.1), c) inner bearing raceway equal to 10% ($\Delta f/f$=0.1)

However, it is relatively difficult to unambiguously define the diagnostic measure most sensitive to all the studied types of tooth gear damage. In the opinion of the authors of this paper the developed methods should be used as complementary methods so as to increase the confidence of diagnostic results.

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