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DIAGNOSTICS OF POWER TRANSMISSIONS SYSTEM WITH TOOTH GEAR

Summary. This paper presents results of laboratory tests that were aimed at detecting early stages of various faults in toothed wheels by measurement and analysis of transverse vibration speed of the transmission gear shafts. In experimental investigation, cracking of the root tooth and chipping of the tooth were detected.

The laser vibrometer Ometron VH300+ was used for non-contact measurement of shaft transversal vibration speed. Gear vibrations were recorded in selected points of gear housing and gear shafts at different speeds and gear loads. Results were analyzed and compared but in this paper is presented only selected examples.

This paper shows that on the basis of the transverse vibration speed of transmission gear shafts, it is possible to detect defects at an earlier stage than on the basis of the housing vibration accelerations. In the case of measuring gear shaft vibration velocity, the way of the signal generated by the defect of a gear wheel (or bearing) is shortened as well as the influence of composed transmittance of the bearing-gear housing system is eliminated.

WV time-frequency analysis and complex continuous wavelet transformations were used for detection. The authors introduced a measure of local tooth damage, which was proportional to the size of damage. The results of research presented in this paper confirmed that the defect's measure is very sensitive to the development of teeth faults.

DIAGNOZOWANIE UKŁADÓW PRZENIESIENIA NAPĘDU Z PRZEKŁADNIAMI ZĘBATYMI

Streszczenie. W artykule przedstawiono wyniki badań doświadczalnych, których celem było diagnozowanie wczesnych stadiów uszkodzeń kół zębatych poprzez pomiar i analizę sygnału drganiowego przekładni. Do pomiarów zastosowano wibrometr laserowy Ometron VH300+ umożliwiający bezkontaktowy pomiar prędkości drgań poprzecznych wałów przekładni.

Na podstawie przedstawionych badań i analiz można stwierdzić, że połączenie zaawansowanych metod przetwarzania sygnałów prędkości drgań poprzecznych wałów zmierzonych w kierunku działania siły międzyzębnej oraz analiz jednocześnie w dziedzinach czasu i częstotliwości lub czasu i skali, umożliwiło efektywne wykrywanie różnych rodzajów uszkodzeń kół zębatych takich jak: wykruszenie wierzchołka zęba zębnika i pęknięcie u podstawy zęba koła.

Do wykrywania uszkodzeń lokalnych kół zębatych zaproponowano miary bazujące na sygnale różnicowym i ciągłej zespolonej transformacie falkowej lub sygnale różnicowym i rozkładzie WV. Opracowane miary wykazują proporcjonalne zmiany wartości do wielkości zaawansowania uszkodzenia zęba, umożliwiając tym samym ich identyfikację.

1. INTRODUCTION

Toothed gears are widely used in systems transmitting mechanical power of transport machine. They are also used in both simple everyday articles and very complex devices. It is evident from research that around 60% of toothed gear failures are caused by wheel defects. There are several main types of defects: chipping of the tooth top, cracking at the tooth root and its partial or complete breakage off as a result, fracture of the toothed wheel rim, fatigue-related chipping of the outer surface of the mating teeth active faces (pitting), and mating teeth surface seizing. Because of the wide application of toothed gears, there is a need for diagnostics of even single wheel pairs, which sometimes human life or business subsistence may depend on. The problem of gear defects is an active area of research for numerous research centers, which largely apply vibration methods [1-11] to address this problem. Despite the fact that there are many publications dealing with the diagnostics of high-power toothed gears, their authors often emphasize the difficulties in clear detection of local wheel faults. The reason for these difficulties is the fact that in the initial phase, these faults do not cause noticeable changes in the general vibration level. The vibration diagnostics of toothed gears most often utilizes piezoelectric acceleration transducers, which are placed on gear casings and very rarely on the wheels themselves. Such placement requires disassembly of the gearbox and application of systems transferring signals from the rotating wheels. This non-contact method is one of the most modern methods of measuring vibration. The laser vibrometer enables, among other things, measurement of vibration speeds of a rotating shaft. The initial surveys of gears with damaged elements demonstrated usefulness of the laser measurements of the rotating shaft transversal vibrations in detection of these defects [6].

Defects of toothed wheels cause local non-stationarities in the vibration signal. Methods of analysis that enable simultaneous observation of the signal in the time and frequency domains proved useful in detection of these non-stationarities, because it is possible to determine the temporal occurrence of the effects generated by the defect. The combination of modern measurement methods, which shorten the signal path from the source to measurement, with analysis in time and frequency (Wigner – Ville distribution) or time and scale domains (Continuous Wavelet Transform – CWT), may allow detection of local gear wheel defects in their early stages.

2. TESTING RIGS AND MEASURING SYSTEM

The experimental tests were conducted in two systems operating as circulating power test rigs; their diagram is presented in figure 1. These rigs allow the tested wheels to operate at different rotational speeds and loads, which are regulated with torsional shafts, tension clutch and a lever with weights. Each rig consists of two gears: the tested one and the closing one, which are characterized by the same gear ratio and wheel spacing. The closing gear is propelled with a 15kW electrical engine.
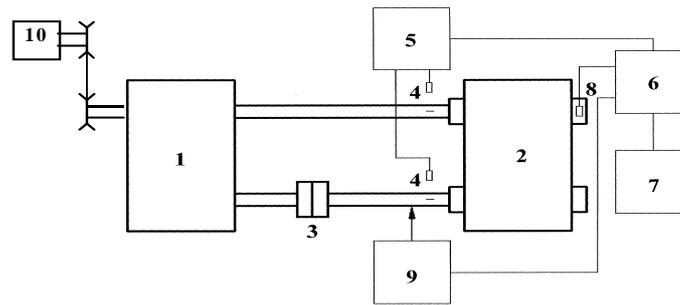
Fig. 1. Diagram of the circulating power test rig: 1 – closing gear, 2 - tested gear, 3 – tension clutch, 4 – sensor of the angular position of the shaft, 5 – logic unit, 6 – signal analyzer DSPT SigLab, 7 – computer, 8 – accelerometer PCB Piezotronics model 353B15, 9 – OMETRON VH300+ laser vibrometer, 10 – propulsion engine

Fig. 2. Schemat stanowiska pracującego w układzie mocy krążącej: 1 – przekładnia zamykająca, 2 – przekładnia badana, 3 – sprzęgło napinające, 4 – czujnik położenia kątowego wałów, 5 –jednostka logiczna, 6 – analizator sygnałów DSPT SigLab, 7 – komputer, 8 – przetwornik przyspieszeń PCB Piezotronics model 353B15, 9 – wibrometr laserowy OMETRON VH300+, 10 – silnik napędzają

Geometric parameters of the toothed wheels installed in the tested gears are presented in Table 1.

Tab. 1

Geometric parameters of the toothed wheels installed in the tested gears

Parameters of toothed gears	Rig 1 (straight tooth gear)	Rig 2 (helical tooth gear)	
		set 1	set 2
number of pinion teeth z_1	16	19	19
number of gear teeth z_2	24	30	30
helix angle β [°]	0	15	15
face width b [mm]	20	56	20
module pitch m_n [mm]	4.5	3.5	3.5
coefficient of pinion addendum	0.864	0.5	0.5
coefficient of gear addendum modification	-0.5	0.295	0.295
Distance between the centers of the two gears [mm]	91.5	91.5	91.5

During the experiments, the tested transmission worked as a reduction gear. The vibration accelerations and speeds of the selected points of the gear housing as well as speeds of transversal vibrations of the shafts were measured. Additionally, the synchronic reference signals, which were in accordance with the shaft rotation, were recorded. The vibration signal and the signal from the synchronous averaging system were sampled with a frequency of 25,600Hz and recorded on the computer's hard drive. During the research, whose purpose was to detect gear defects, the oil temperature in the gearbox was maintained at 45 ±2°C. Only during the tests conducted in rig 2, when the wheel set no. 1 was installed in the gearbox, was the oil temperature set to 55 ±2°C on account of the magnitude of transmitted power.

The scope of the survey included measurements in different stages of defect development, and at different rotational speeds and loads. The performance of active experiments, whose purpose was to record the vibration signals in different stages of defect development, required assembly and disassembly of the gearbox after each measurement series. As part of the project, the authors also

carried out a numerical experiment, whose goal was to check the possibility of detection of pitting that occurs on active tooth faces. A few hundred vibration measurements were performed during the experimental phase.

3. DETECTION OF TOOTH TOP CHIPPING

The tests, whose purpose was to detect tooth top chipping, were carried out on rig 1. Tooth chipping was modeled by shortening the tooth in successive phases by 1 mm (Figure 2). In case of meshing of the damaged tooth, this shortening resulted in a decrease in the tooth contact ratio (ε_α). Its nominal value equaled 1.33. The pinion rotation rate during the tests equaled 2,700 rpm and the gears were loaded with a torque of M_h=207 Nm.

ε_α=1.21 ε_α=1.08 ε_α=0.96 ε_α=0.82
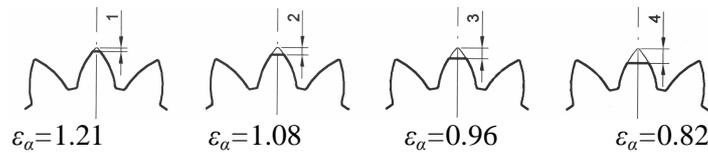
Fig. 2. Local pinion tooth damage – tooth top chipping (1,2,3,4 mm)
Rys. 2. Lokalne wykruszenie wierzchołka zęba zębnika (1,2,3,4 mm)

Measurements were conducted with a piezoelectric transducer of vibration accelerations and the laser vibrometer, which was used to measure the vibration speeds of rotating shafts and selected points on the housing in the direction of mesh force, as well as horizontally and vertically. Signal analysis was conducted in order to detect pinion tooth chipping . During the analysis, synchronous averaging with the pinion rotation period was conducted; this process enabled removal of components that are unrelated to the pinion rotation, and improved the signal to noise ratio. Based on the time graph of the averaged signal of speeds of the pinion shaft transversal vibrations (Figure 3), it is difficult to determine whether tooth chipping occurred. It was possible to detect several local maximums, and essentially each of them could have originated from this defect.
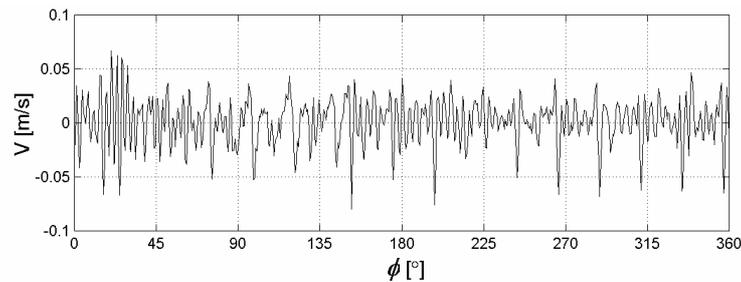
Fig. 3. Signal of pinion shaft transversal vibration speeds averaged with pinion revolution period and measured in the mesh force direction – 2 mm pinion tooth chipping
Rys. 3.Uśredniony sygnał prędkości drgań poprzecznych wału zębnika zmierzony w kierunku siły międzyzębnej – wykruszenie wierzchołka zęba zębnika 2 mm

Therefore, the Wigner-Ville pseudo-transform was applied to generate a time – frequency distribution of the signal.

$$WV(t,f) = \int_{-\infty}^{+\infty} x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right) w(\tau)\, e^{-j2\pi f\tau} d\tau, \tag{1}$$

where: $x^*(t)$ – composite signal coupled with $x(t)$, $w(t)$ – weighting function similar to the time window used in short-term Fourier Transform.

In the case of signal analysis of pinion shaft transversal vibration speeds, which were measured in the direction of the mesh force and averaged with the pinion rotation period, the presented method enabled clear detection of 3 mm and 4 mm tooth chippings. These chippings were also detectable by the proposed method through the analysis of signals of pinion shaft transversal vibration speeds measured in the vertical direction; however, detection of the 3 mm chippings was not possible on the basis of measured vibrations of remaining points. Detection of 1 or 2 mm tooth chippings was, in this case, not possible. Considering the *WV* time – frequency distribution of the averaged signals of pinion shaft transversal vibration speeds, it was noted that the greatest energy of the signal occurred in meshing frequency bands f_z and its harmonics. These components mask the low-energy disturbance caused by the fault. To highlight this defect, a differential signal according to the algorithm shown in figure 4 was generated [6,10]. However, it was still hard to distinguish in the signal presented in figure 5 the disturbance, which might originated from the defect in question. *WV* time – frequency analysis of the differential signal was performed (Figure 6). The local tooth damage generated in differential signal wide band impulse therefore the authors observed an increase of amplitude in the 0-4500 Hz band, which occurred in the range of the turn angle corresponding to the mating of the damaged pinion tooth.
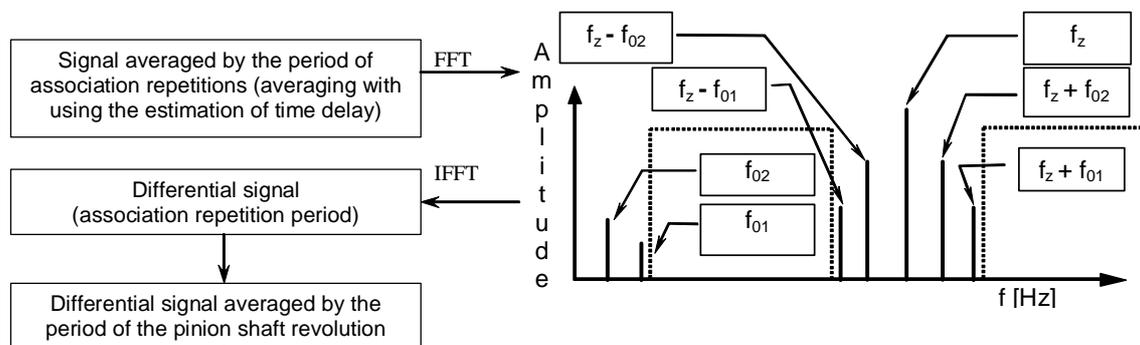
Fig. 4. Algorithm for the differential signal; f_{o1} – pinion rotation frequency , f_{o2} – gear rotation frequency, f_z – meshing frequency
Rys. 4. Algorytm tworzenia sygnału różnicowego; f_{o1} – częstotliwość obrotu zębnika, f_{o2} – częstotliwość obrotu koła, f_z – częstotliwość zazębienia
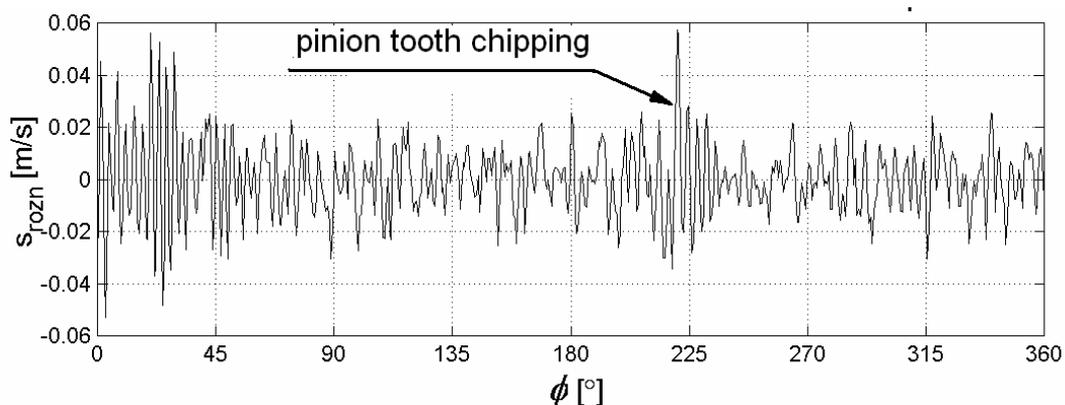
Fig. 5. Differential signal on the base of averaged signal presented on the figure 3 – 2 mm pinion tooth chipping
Rys. 5. Sygnał różnicowy otrzymany na podstawie sygnału zaprezentowanego na rysunku 3 – wykruszenie wierzchołka zęba zębnika 2 mm
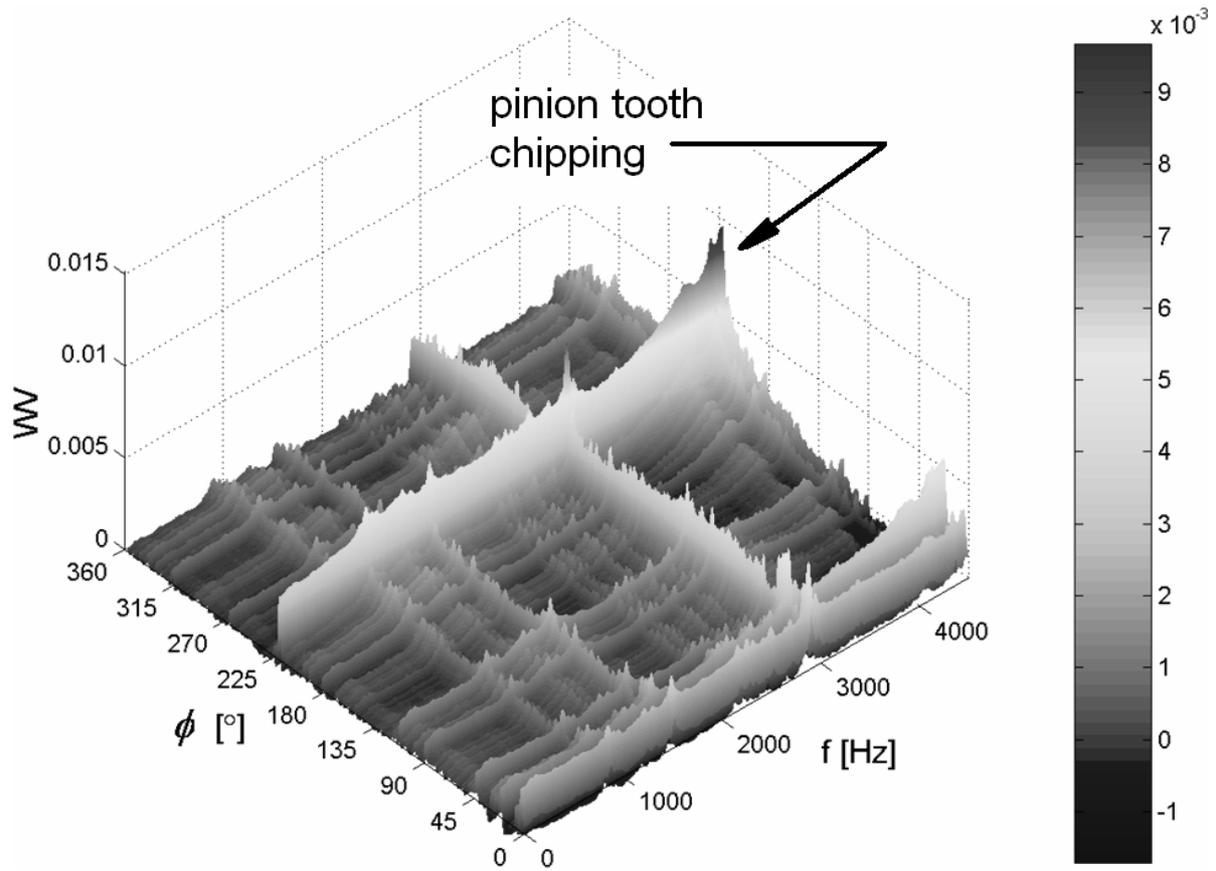
Fig. 6. WV time – frequency distribution of the differential signal – measurement of the pinion shaft vibration speeds in the direction of the mesh force – 2 mm pinion tooth chipping

Fig. 6. Czasowo- częstotliwościowy rozkład WV sygnału różnicowego– pomiar prędkości drgań poprzecznych wału zębnika – wykruszenie wierzchołka zęba zębnika 2 mm

This increase also occurred in the presence of different tooth chipping sizes, even when the chipping size equaled 1 mm. In order to facilitate interpretation of the obtained results, the authors summed the discrete values of the *WV* distribution (1) according to the equation:

$$S_{WV}(\phi) = \sum_{k_{WV}=A}^{B} WV(l_{WV}, k_{WV})$$
(2)

where: $WV(l_{WV}, k_{WV}) = WV(t, f)$, l_{WV}, k_{WV} – discrete values of time and frequency, respectively,
 A, B – discrete values corresponding to limit frequencies of the summing interval f_A, f_B, respectively.

The summation was performed for the frequency interval $f_A \div f_B$ ($f_A = 0$ Hz, $f_B = 4500$ Hz $\approx 6,5 f_z$), in which the *WV* distribution values dominated in the angle range corresponding to the mating of the damaged tooth. The local maximums corresponding to the chipping of the pinion tooth top are clearly visible on the proposed *WV* distribution sum (Fig. 7), which makes this fault easy to detect.
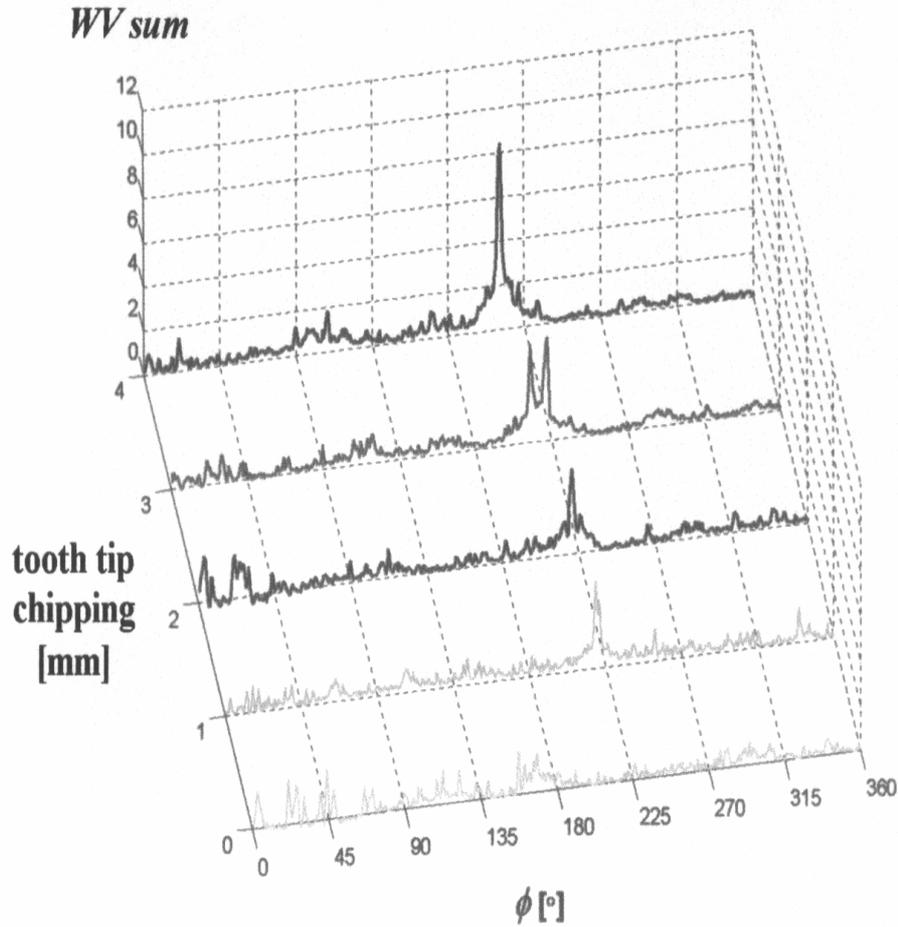
Fig. 7. Sum of *WV* time – frequency distribution in the 0-4500Hz band, performed from the differential signal of the pinion shaft vibration speed measured in the inter-tooth direction

Rys. 7. Suma rozkładu czasowo-częstotliwościowego WV w paśmie 0÷4500 [Hz] wykonana z sygnału różnicowego prędkości drgań wału zębnika zmierzonego w kierunku działania siły międzyzębnej

The purpose of the additional analyses was to find a measure that is sensitive to the development of the tooth top chipping. The authors propose the non-dimensional measure M_{wWV}, which is determined from the following equation [10]:

$$M_{wWV} = \frac{S_{WVu}}{\overline{S}_{WVzw0}} \,, \tag{3}$$

where: S_{WVu} – maximal value in $S_{WV}(\phi)$ for $\phi \in \langle 0^0, 360^0 \rangle$, $\overline{S}_{WVzw0}$ – average value z_D of the greatest maximal local values $S_{WV}(\phi)$, in the interval: $\phi \in \langle 0^o, \phi_u - 0.5\phi_z \rangle \cup \langle \phi_u + 0.5\phi_z, 360^o \rangle$ for gears without faults (new), ϕ_z – turn angle of the toothed gear corresponding to the base pitch, ϕ_u – turn angle of the toothed gear at which S_{WVu} occurs, z_D – number of teeth of the tested toothed gear.
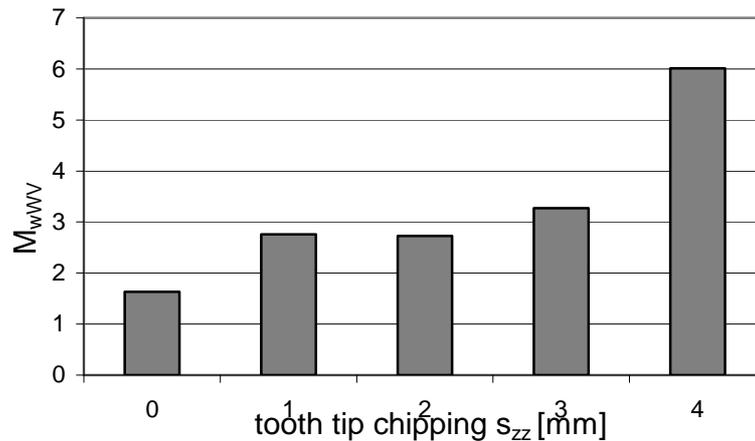
Fig. 8. Changes in the proposed tooth chipping measure M_{wWV} based on the sum $S_{WV}(\phi)$ as a function of tooth tip chipping – results of the experiments.

Rys. 8. Zmiany zaproponowanej miary wykruszenia zęba M_{wWV} bazującej na sumie $S_{WV}(\phi)$ w funkcji skrócenia zęba zębnika - wyniki badań doświadczalnych

Figure 8 presents the M_{wWV} values as a function of pinion tooth shortening. The proposed measure identifies the occurrence of even insignificant 1 mm chipping: a 70% increase in M_{wWV}. Therefore, we conclude that the proposed measure is sensitive to the occurrence of chipping in early stages. A decrease in the tooth contact ratio, as an effect of tooth top chipping, results in an increase in the proposed measure growth dynamics.

Applying a similar procedural algorithm, a measure based on the Continuous Complex Wavelet Transform was derived from the following equation:

$$S(\phi) = \sum_{l=A}^{B} C(l,k) \tag{4}$$

where: A,B – lower and upper limits of the sum scale.

The conducted tests demonstrated the utility of wavelet analysis [1,4,7,10,11,12] in diagnostics of the tooth top chipping (Figure 9) and the fracture at the tooth root [10].

4. CONCLUSION

The conducted research and analyses illustrated that the application of advanced methods of signal processing of the shaft transversal vibration speed and utilization of analyses simultaneously in time and frequency or time and scale domains (CWT) enabled the detection of the following gearbox faults: chipping of the tooth top, fracture at the tooth root as a result, fracture of the tooth wheel rim. The authors introduced a measure of local tooth damage, which was proportional to the size of damage. The results of research presented in this paper confirmed that the defect's measure is very sensitive to the development of teeth faults.
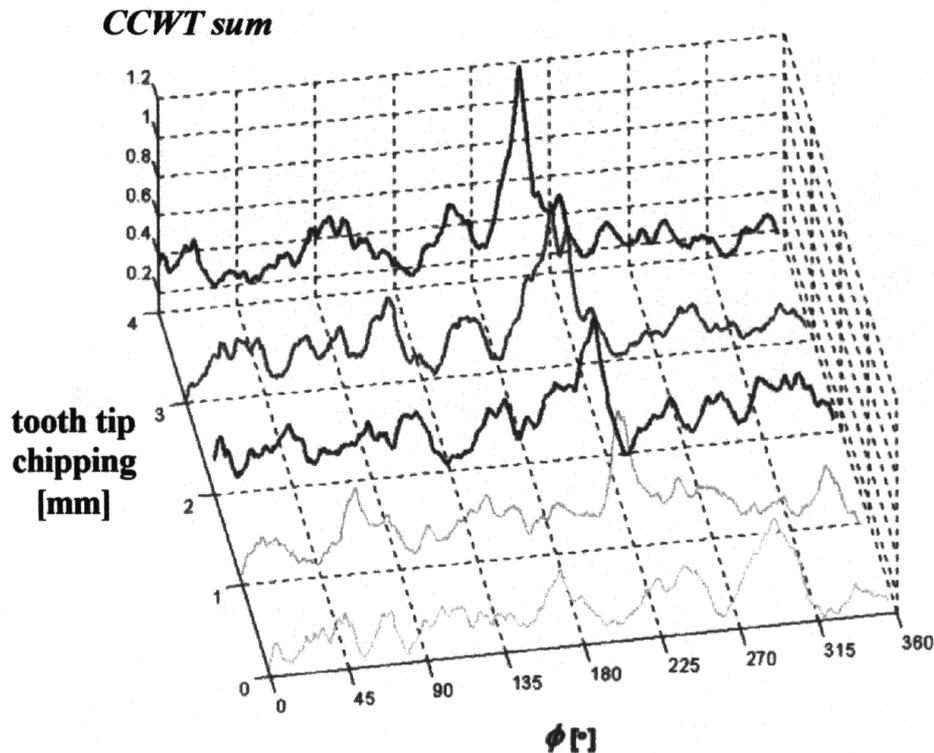
Fig. 9. Sum of CCTW coefficient modulus in the case of cGaus4 wavelet application; differential signal; measurement in the direction of the mesh force; A=1, B=25

Rys. 9. Suma modułów współczynników CCWT w przypadku zastosowania falki cGaus 4 - sygnał różnicowy prędkości drgań poprzecznych wału zębnika w kierunku działania siły międzyzębnej, A=1, B=25

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