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CLASSIFICATION OF THE DEGREE OF CHIPPING TIP OF THE TOOTH IN A GEAR WHEEL BY USING THE FUZZY LOGIC AND THE CONTINUOUS WAVELET TRANSFORM

Summary. This article presents the tests results showing the construction of the local damages classifier of the transmission gear teeth, built on the basis of the fuzzy logic. The tested object was the transmission gear with straight teeth, working on the circulating power FZG stand. The tests included the gears with the undamaged teeth and with the locally damaged teeth in the form of the tooth top crumbling. The construction of the systems diagnosing the local damages of the teeth was also proposed. To achieve this aim, the vibration signals which had undergone proper filtration and processing were used.

KLASYFIKACJA STOPNIA WYKRUSZENIA ZĘBA KOŁA PRZEKŁADNI PRZY UŻYCIU LOGIKI ROZMYTEJ I CIĄGŁEJ TRANSFORMATY FALKOWEJ

Streszczenie. W artykule przedstawiono wyniki prób mających na celu budowę klasyfikatora lokalnych uszkodzeń zębów kół przekładni, zbudowanego w oparciu o logikę rozmytą. Obiekt badań stanowiła przekładnia zębata o zębach prostych, pracująca na stanowisku mocy krążącej FZG. Badaniami objęto przekładnie z kołami bez uszkodzeń oraz z lokalnymi uszkodzeniami zębów w postaci wykruszenia wierzchołka zęba. Zaproponowano również sposób budowy systemów diagnozujących lokalne uszkodzenia zębów kół. Do tego celu wykorzystano sygnały drganiowe poddane odpowiedniej filtracji oraz przetwarzaniu.

1. INTRODUCTION

Toothed gears are often elements, on which human lives depend. They are used in most transmission gears, both in various machines as well as in means of transport. The toothed gear is a very important part of the kinematics chain of the power transmission system between the engine and the energy receiver. According to literature [7], about 60% of damages that it is affected by are caused by the toothed gear failure. It is especially important to create such methods that will enable the detection of the different kinds of toothed wheel damages in their early stages.

The spreading speed of the vibroacoustic disturbance created by the change of the object state causes that the vibroacoustic methods are specially useful in cases of the damage appearance [1]. So far, there are no ready solutions to be found in literature in the field of diagnosis of the teeth damages creation and development that would enable to identify this state still in the early stages of development, as not to let the dangerous failure appear. Some examples connected with the usage of artificial intelligence in the diagnostic tasks have recently appeared in literature [2]. Examples in literature shows that the most difficult aspect in the process of designing systems using the artificial intelligence is the necessity of approaching each task individually. Up till now, no explicit guiding principles connected with the ways of such systems creation and teaching have been worked out. Among the artificial intelligence methods, we can distinguish the fuzzy logic [8]. In this article the proposition of the fuzzy logic usage in the diagnostic aims will be presented.

2. THE INTRODUCTION TO THE FUZZY LOGIC

The fuzzy logic is a very effective way of converting the unsure and inaccurate information i.e. such logic, that appears in practice [9]. Regarding its features, it can be successfully used in the state of technical objects diagnosis systems. The basis for the fuzzy algorithms was widely described in literature [8]. The structure of the fuzzy model has three data block elements:

- fuzzification
- inference
- defuzzification

The structure of an example fuzzy model, with two inputs and one output is presented in fig. 1 [15].

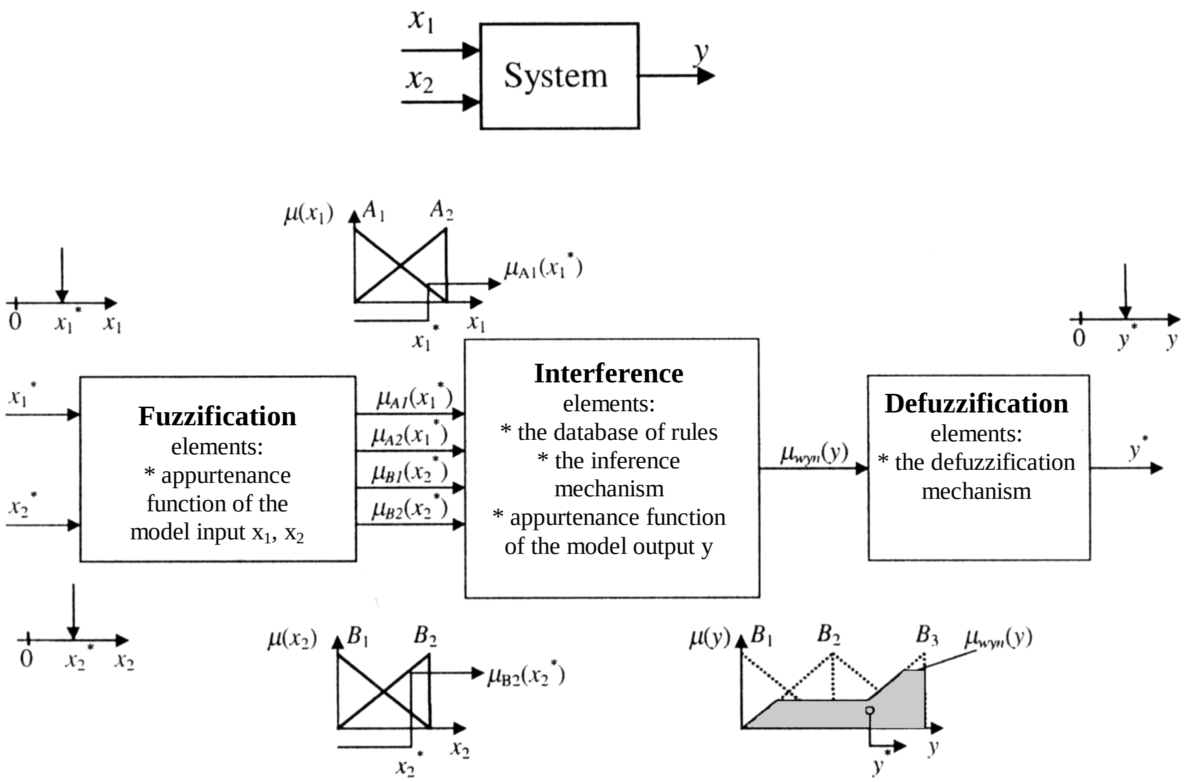

Fig. 1. The example structure of a fuzzy model
Rys. 1. Przykładowa struktura modelu rozmytego

For acute input values x_1^* and x_2^* we mark the degree of appurtenance $\mu(x_1^*)$ and $\mu(x_2^*)$ to appropriate fuzzy sets A and B. Such process takes place in a data block of fuzzification, where appurtenance functions to the fuzzy sets of successive system inputs are defined. Appurtenance functions must be precisely defined in terms of quality (the type of the function) and in terms of quantity (parameters, the coefficients of function). On the basis of the appurtenance degree of the inputs, the next block of fuzzy system marks the resulting appurtenance function $\mu_{wyn}(y)$. Inference block must contain the following elements:

- the database of rules,
- the inference mechanism,
- appurtenance function of the model output.

In the database of rules we find the cause-and-effect relationship of the output from the model inputs, for example, rule 1: if $(x_1 = A_1)$ and $(x_2 = B_1)$ then $(y = C_1)$.

In the inference mechanism we calculate the degree of fulfilment of all of the rules, the degree of conclusion activation for every rule and the result form of the output appurtenance function $\mu_{wyn}(y)$.

In the last block of the fuzzy system on the basis of the resulting output appurtenance function we mark the acute output value y^*. The detailed description of the methods used to mark the output value was presented in paper [8].

3. THE DESCRIPTION OF THE EXPERIMENT

In conducted experiments an attempt was made to build a degree of damage classifier for toothed gear teeth with the use of fuzzy logic. The object of the research was a toothed gear with straight teeth working on the post of circulating power, where the number of teeth in the pinion and the wheel was 16 and 24.

The signals of the transverse vibration speed for the shaft of the wheel measured on the post of circulating power (fig.2) were the basis for building the models of the stage of the teeth damage in toothed gears for designed classifiers.

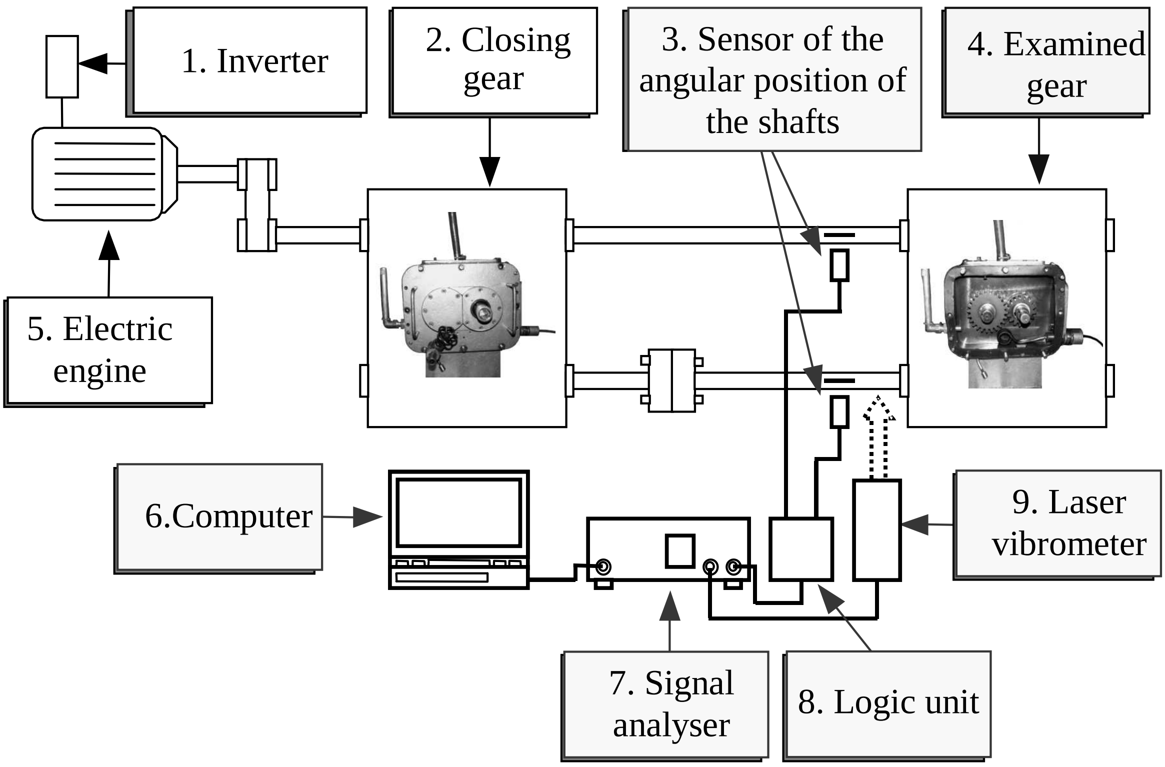

Fig. 2. Scheme for the measuring system (1-inverter, 2-closing gear, 3 sensor of the angular position of the shafts, 4- the examined gear, 5- electric engine, 6-computer, 7- the signal analyser, 8- logic unit, 9- laser vibrometer)

Rys. 2. Schemat układu pomiarowego (1-falownik, 2-przekładnia zamykająca, 3-czujnik położenia kątowego wałów, 4-przekładnia badana, 5-silnik elektryczne, 6-komputer, 7-analizator sygnałów, 8-jednostka logiczna, 9-wibrometr laserowy)

The measurement was conducted on an undamaged gear, as well as with modelled damages in the form of tooth top crumbling. The modelled damage values of 0.75 mm, 1.5 mm, 2 mm [7]. Each of the measured series was conducted for toothed gear working in gear rotational values of 900 rotations per minute and 1800 rotations per minute, and with the loads of 2.58 MPa, and 3.85 MPa.

The registered vibration signals undergone the treatment of low-pass filters in the range of 6 and 12 kHz – filters number 1 and 2; filters enabling the achievement of residual and differential signals – filters number 3 and 4; filter in the range of 0.5-1.5 of meshing frequency – filter number 5.

The residual signals were achieved by deleting those bands from the spectrum which included the rotary components of the wheels shafts and their harmonics and component meshing frequencies and their harmonics, and the differential were achieved by additionally deleting the bands around the meshing frequency and their harmonics containing the sidebands connected with rotary frequencies of toothed wheels[21,22]. Next, with the use of the reversed Fourier transform we got time signals. In the next stage the vibration signals were achieved with the use of five filters undergone the treatment with the continuous wavelet transform (CWT) [3].

Wavelet analysis involves the decomposition of signal and showing it in a linear form of base function combinations, known as wavelets [4]. The feature differentiating this method of analysis from other methods is multilevel decomposition of the signal, changeable distribution in the domain of time and frequency, the possibility of application of base functions other than harmonic functions [16]. The continuous wavelet transform is defined as follows [3,4]:

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

where: $\psi_{a,b}(t)$ - wavelet function, wavelet, a - scale parameter, connected with the location in the frequency domain, $a \in R^{+}$, $a \neq 0$, b - shift parameter in the time domain, $b \in R$.

The frequency of the wavelet is regulated with the use of scale parameter a, and with the use of parameter b it is possible to examine the local features of time course [3].

This method, due to the possibility of adjustment of the window width to the analysed frequency range, enables the examination of non-stationary signals. For the slowly-changing courses the window expands in the time domain, whereas by high frequencies it narrows, keeping the constant surface area [3]. The appropriate choice of base wavelet and the array of the scale value is the necessary condition to the correctness of the diagnosis process of the technical state of the object with the use of wavelet analysis.

In order to describe the character of the changes of signal amplitude affected by CWT for 20 scales chosen in the initial analysis, an efficiency value was marked (figure 3). The marked value described the change process of the CWT distribution in time domain. On the basis of the initial research the following base wavelets were chosen for the experiment [7,8]:
- Daubechies wavelet (wavelet number 9),
- Morlet wavelet (wavelet number 37),
- reverse bi-orthogonal wavelet 3.7 (wavelet number 50).

On the basis of the obtained results an attempt was made to determine the function of input appurtenance. The sequence of actions by determining the characteristic points for input appurtenance function of diagnostic system was shown in a schematic way on figure 4.

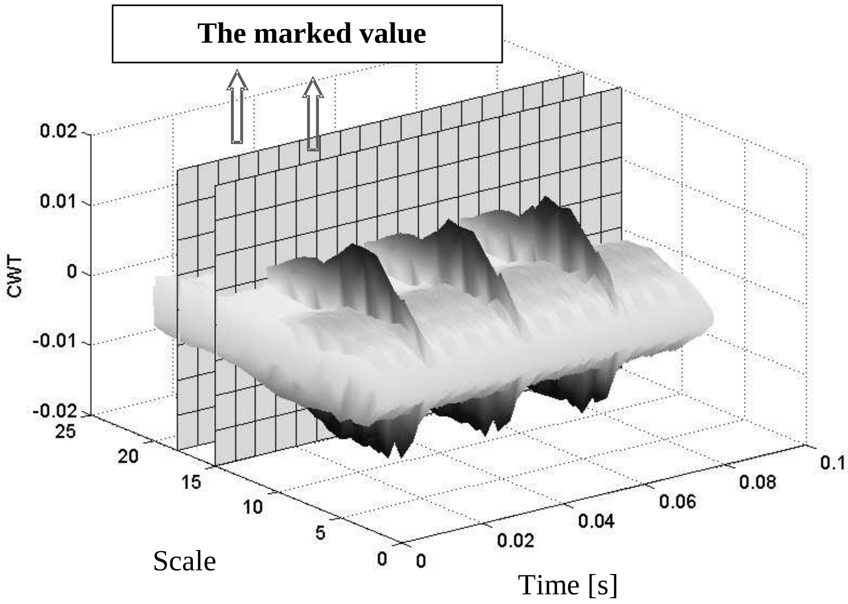

Fig. 3. The way of amplitude CWT change description
Rys. 3. Sposób opisu charakteru zmian amplitudy CWT

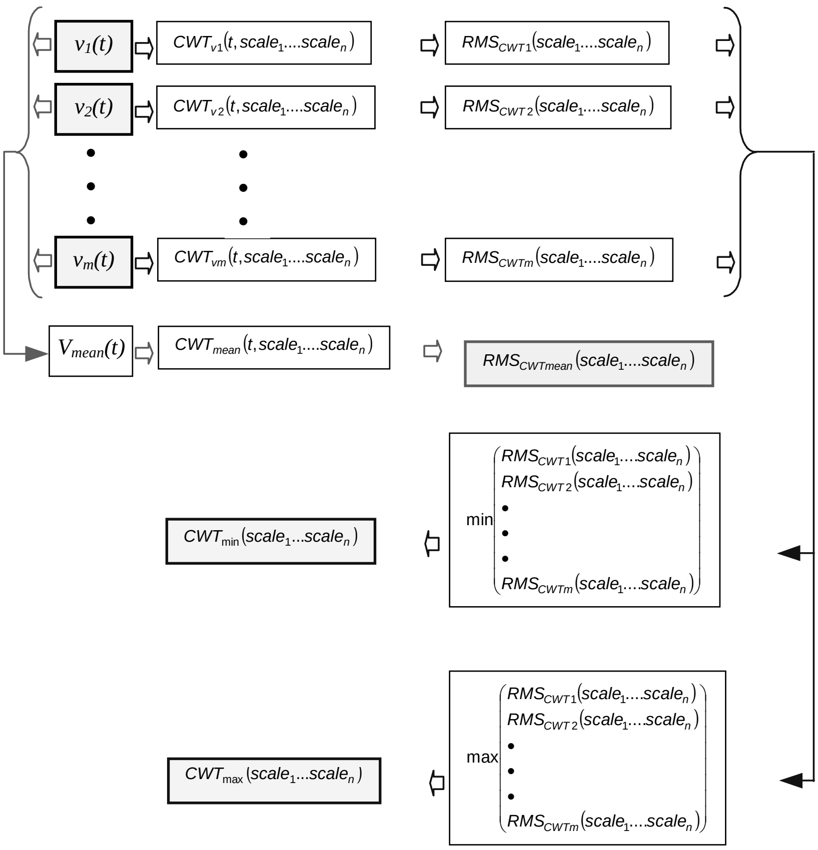

Fig. 4. The way a classifier model using fuzzy logic is built
Rys. 4. Sposób budowy wzorców dla klasyfikatora wykorzystującego logikę rozmytą

The estimates marked in such a way were used to determine the characteristic input appurtenance functions. Using the literature examples a triangular function was chosen for research as an input appurtenance function (fig.5) The way characteristic points for a triangular function are marked were assumed according to table 1.

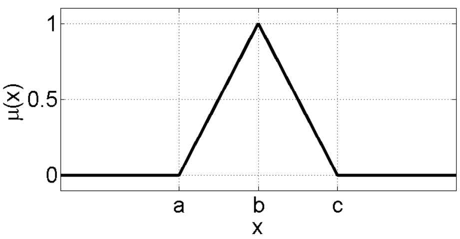

Fig. 5. A chosen input appurtenance function
Rys. 5. Wybrana funkcja przynależności wejść

Tab. 1

The way characteristic points for input appurtenance function are marked

The way characteristic points for input appurtenance function are marked:	
„A”	**„B”**
$a = \min(CWT(v))$	$a = \min\begin{pmatrix} \min(CWT(v)) \\ \max(CWT(v)) \\ CWT(v_{usr}) \end{pmatrix}$
$c = \max(CWT(v))$	$c = \max\begin{pmatrix} \min(CWT(v)) \\ \max(CWT(v)) \\ CWT(v_{usr}) \end{pmatrix}$
$b = \frac{\min(CWT(v)) + \max(CWT(v))}{2}$	$b = \min(CWT(v))$ lub $b = \max(CWT(v))$ lub $b = CWT(v_{usr})$ gdzie: $a < b < c$

It should be pointed out that, the best of cases would be the one, where each following class would not have common element (fig.6a) In such a situation it would no longer be necessary to use the fuzzy logic system, one estimate would be enough, on the basis of which the respective states would be classified. The opposite example is shown in fig.6b. In this case the range of value changeability for each class includes in each other in whole, which makes the correct working system elaboration impossible.

In the introductory part of the experiment input appurtenance functions for 20 analysed scales were marked and they were to constitute the inputs of the classification system. The calculations were revised for vibration signals which undergone further filtration with the use of 5 filters and with the use of 3 base wavelets. In total, 60 sets of appurtenance functions for 20 inputs were achieved. In the next stage of the experiment, having analysed every set, 30 new sets were chosen, among which there were only those best adjusted to the process of input classification. In this process the basic idea was the one shown in figure 6. For the purpose of comparison additionally one set was added, which constituted of all scales marked in CWT process.

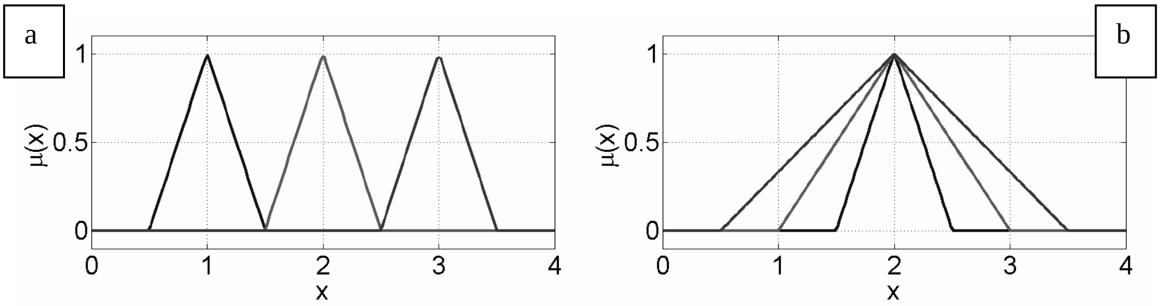

Fig. 6. Model input appurtenance functions: a) the best of cases b) the worst of cases
Rys. 6. Wzorcowe funkcje przynależności wejść: a) przypadek najlepszy, b) przypadek najgorszy

Also in case of outputs of the system using fuzzy logic for diagnostic purposes of toothed gear, two methods of fuzzification (figures 7 and 8).

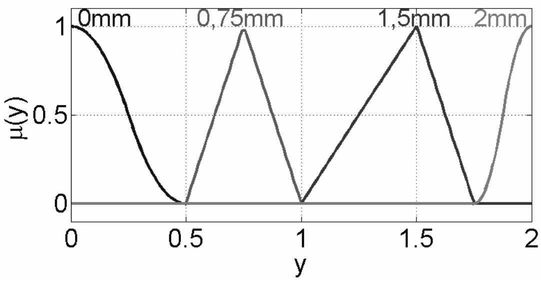

Fig. 7. Way number 1 of construction of the fuzzy outputs of the fuzzy logic system for a damage in the form of the chipping tip of the tooth
Rys. 7. Sposób „1” budowy rozmytych wyjść systemu logiki rozmytej dla uszkodzenia w postaci wykruszenia wierzchołka zęba

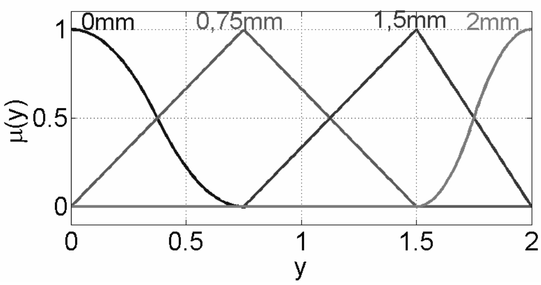

Fig. 8. Way number 2 of construction of the fuzzy outputs of the fuzzy logic system for a damage in the form of the chipping tip of the tooth
Rys. 8. Sposób „2” budowy rozmytych wyjść systemu logiki rozmytej dla uszkodzenia w postaci wykruszenia wierzchołka zęba

The determination of the damage level of the teeth of the gear was the main aim of conducted diagnostic process. The simultaneous damages modelled in the experiment constituted classes, for which the diagnostic system was to qualify a given damage. The classes determined the position of the points for which the output appurtenance function equalled 1. It was assumed in the experiments the sigmoid appurtenance function was used for the terminal classes, and for other classes a triangular function was applied. The assumed ways of determination of the characteristic points of output appurtenance function are visible in figures 7 and 8.

The research conducted with various methods of input and output fuzzification was to show the influence of the result of the classification process of the type and degree of teeth damage of toothed gear.

- $Q = 2{,}58$ MPa, $n = 900$ rotation/minute,
- $Q = 2{,}58$ MPa, $n = 1800$ rotation/minute,
- $Q = 3{,}85$ MPa, $n = 900$ rotation/minute,
- $Q = 3{,}85$ MPa, $n = 1800$ rotation/minute.

The points of machine work were in accordance with those chosen in the process of registration vibration on the spot of rotating power FZG.

Additionally experiments were conducted with the use of classifiers working independently to the load and rotation speed of the shaft of the toothed gear wheel.

In the time of construction of the rule basis of fuzzy logic two ways presented in figures 9 and 10 were used.

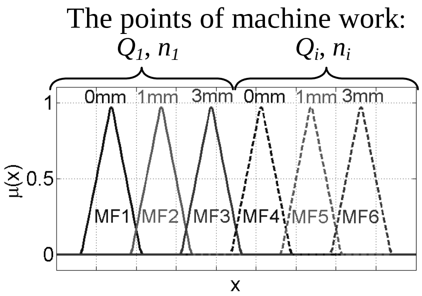

Fig. 9. System “I” of the rules construction system of fuzzy logic, MF1...6 – following appurtenance functions
Rys. 9. System „I” budowy reguł systemu logiki rozmytej, MF1...6 – kolejne funkcje przynależności

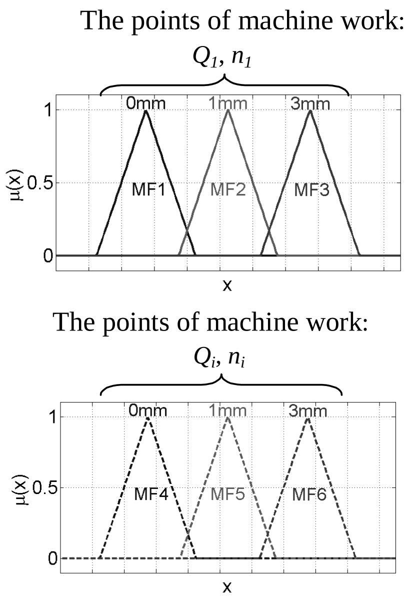

Fig. 10. System “II” of the rules construction system of fuzzy logic, MF1...6 – following appurtenance functions
Rys. 10. System „II” budowy reguł systemu logiki rozmytej, MF1...6 – kolejne funkcje przynależności

In type “I” system for each input all existing common points of the machine work were coded, whereas in type “II” of the system each of the inputs was multiplied by the number of analysed work points of toothed gear. This method is analogical to the one used in time of research on classification of the degree of toothed gear damage working in one load moment and one rotation speed of the gear shaft.

The set of rules was described as follows:

if x_1 is A_1 and x_2 is A_2 ... and x_k is A_k then it is class 1,

if x_1 is B_1 and x_2 is B_2 ... and x_k is B_k then it is class 2,

if x_1 is Z_1 and x_2 is Z_2 ... and x_k is Z_k then it is class N,

where:

$x_1 ... x_k$ - are values of estimates marked in a given part of the spectrum, k - number of inputs of the diagnostic system, $A_1 ... A_k$, $B_1 ... B_k$, $Z_1 ... Z_k$ - defined for each input separately value range of estimates marked in a given part of spectrum, which is the equivalent for a given damage class,

class 1, class 2...class N - recognisable class of teeth damage in toothed gear,

N - the number of classes of the damages of teeth in a toothed gear.

3. THE RESULTS OF THE EXPERIMENT

In the first series of the conducted research systems were built to classify the degree of damage of the teeth in toothed gear working with a given rotation speed and load. For classification systems of the degree of tooth top crumbling the results had quite a wide range. In most cases of the used system types as well as different sets of models the best results were to be found in the region of up to 20% of the measuring error.

Because of the fact that the toothed gears in power transmission systems usually work with different speeds and loads, it was decided that in the next research the tests would be conducted with the use of diagnostic systems diagnosing the degree of tooth top crumbling of a toothed gear working with different speeds and loads. Tab. 2 presents the best results.

Tab. 2

A set of the best results of classification of tooth top crumbling of a toothed gear working with one rotation speed of shaft and with one load

	Filter number														
	1			***2***			***3***			***4***			***5***		
	Wavelet number														
	9	***37***	***50***	***9***	***37***	***50***	***9***	***37***	***50***	***9***	***37***	***50***	***9***	***37***	***50***
I-A-1	8,72	9,40	8,84	9,26	11,29	10,75	11,44	11,71	11,70	11,44	11,44	11,70	10,61	11,29	10,49
I-A-2	8,72	9,40	8,84	9,27	11,29	10,47	11,44	11,85	11,70	11,44	11,58	11,70	10,61	11,29	10,49
I-B-1	18,87	17,63	18,46	14,79	12,90	16,73	13,72	14,77	15,45	16,03	17,86	15,31	20,24	22,12	26,20
I-B-2	19,82	19,13	18,33	15,47	15,07	17,91	15,07	15,46	18,86	15,90	20,49	20,64	20,20	24,85	30,55
II-A-1	8,72	9,40	8,84	9,26	11,29	10,75	11,44	11,71	11,70	11,44	11,44	11,70	10,61	11,29	10,49
II-A-2	8,72	9,40	8,84	9,27	11,29	10,47	11,44	11,85	11,70	11,44	11,58	11,70	10,61	11,29	10,49
II-B-1	18,87	17,63	18,46	14,79	12,90	16,73	13,72	14,77	15,45	16,03	17,86	15,31	20,24	22,12	26,20
II-B-2	19,82	19,13	18,33	15,47	15,07	17,91	15,07	15,46	18,86	15,90	20,49	20,64	20,20	24,85	30,55

In case of I-A-1, I-A-2, I-B-1, I-B-2, II-A-1, II-A-2, II-B-1, II-B-2 system type analysis a small influence was noticed of the used in the construction models of filtration types and base wavelet types on the correctness of the classification process of the degree of tooth top crumbling. The appearing differences for a given type system had the value of 3÷15%. The smallest error was achieved in case of system type I-A-1 which used the data achieved with the use of filter number 1(8.72÷9.40%). Slightly higher results were observed in case of the use of other filters. For systems using filters number 3 and 4, the same error values were noted. After a change of system to I-B-1 the results got significantly worse. The smallest error value was noted for a system using filter 2 and wavelet No.37 (12.90%). The highest error value equalling 26.20% was shown on the classifier using the data achieved with the use of filter 5 and wavelet No.50. During the comparison of the achieved results with the results of I-A-1 it can be noticed a double worsening of the correctness in case of many types of used models. A similar situation appears in the comparison analysis of systems I-A-2 and I-B-2. The achieved results for systems I-A-2 are in most cases twice lower in comparison to the second analysed method. The smallest mistake 8.72÷9.40% is visible with the use of filter No.1. In case of the use of filters 3 and 4 for next tested wavelets a similar error was achieved. After the change to system I-B-2, a slight decrease of the correctness of the classification of the degree of tooth top crumbling was noted. For data achieved with the use of filter No. 2 the closest accordance with the model was achieved. In this case error was in the range of 15.07% for wavelet No.37 up to 17.91% for wavelet No.50. The highest error values were recorded for filter number 5. The highest error value was 30.55% for wavelet No.50. The change of system type using fuzzy logic with the aim of diagnosis of the degree of tooth top crumbling from A-I to II-A-I, from I-A-2 to II-A-2, from I-B-1 to II-B-1 and from I-B-2 to II-B-2 does not influence in any way on the achieved results of classification. When comparing the systems of type I-A-1 with I-A-2 it was noticed that in case of the use of filter 1 and 5 the results achieved for both systems are the same for three wavelet types. The lowest error value equalling 8.72% was recorded for filter No.1 and wavelet No.9.

The highest error value for I-A-1 system equalled 11.71%, and for system I-A-2 equalled 11.85%. In both of those cases the highest error values were recorded for filter 3 and wavelet No.37. Analogical situation occurred in case of comparison of systems II-A-1 with II-A-2. The change of the applied classifier type from I-B-1 to I-B-2 caused the rise of error value. The lowest error values were observed for filters 2 and 3 and the highest for filter No.5. In case of system type I-B-1 it was an error range of 12.90-15.45% and 20.24-26.20% and for system I-B-2 15.07-18.86% and 20.20-30.55%. In case of systems II-B-1 and II-B-2 the results were analogical.

To sum up it may be stated that the conducted experiments have shown the possibility of building a correctly working classifiers of the tooth top crumbling degree of gear wheel with the use of fuzzy logic.

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