An application of neural network in recognizing of the tooth contact of spiral and hypoid bevel gears

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Abstract

The special computer system KONTEPS for calculation of spiral and hypoid bevel gears generally supports technology for the conventional and CNC machines (milling machines). In this system environment, the special computer application generates solid or surface models of gears by cutting simulation. Other computer application, based on Matlab functions and methods of artificial intelligence, supports the tooth contact development. The special classifiers which allow to recognize the tooth contact, select the first, second and third order of changes and support the technologist in manufacturing process. This paper describes computerized integration of design and manufacturing of the spiral and hypoid bevel gear supported by the artificial intelligence.

KEYWORDS: **spiral bevel gears**, **tooth contact**, **neural network**

Introduction

The tooth contact analyses is one of the important elements during development process of the spiral and hypoid bevel gears [1, 2, 3, 4]. The size, orientation and shape are the main features of the tooth contact. This analysis can be done in CAD environment when CAD system is used to generate solid models of gears by the cutting simulation [5,6] or by numerical methods supported on Litvin theory [1, 2]. In each case there are the theoretical solutions in computer environment without any errors which exist during cutting on the milling machines as kinematic errors of the machine, setup errors, fixture errors, blank errors, cutter errors etc. These factors are the reasons that the tooth contact of the cutting gears is different than the theoretical approach. In order to correct the tooth contact, the first, second and third order of changes are introduced. The first order of changes (proportional changes) are used during cutting by a technologist in the machine setup without special calculations, based on practical recommendations and experiences only, obviously supported on the theory of gears. Second order of changes is used when the first order changes are not effective. They are determined during technological calculations also as proportional changes and they control the features of the tooth contact as an example: spiral angle, tooth profile, bias in, bias out, etc. Third order of changes requires the new geometrical and technological calculations. It means that they will have new geometrical dimensions of gears which are slightly different from the previous geometry such as tooth proportions, addendum and dedendum angle, pressure angle, etc. In this case the gears follow the same procedure in a development process: first, second and third order changes. Steering of tooth contact requires in depth knowledge and experience about the spiral bevel gears. Therefore, it is necessary to provide the technologist and the operator new tools to support them in such development process.

Tooth contact development and identification of tooth bearing can be transferred to artificial intelligence area supported by a neural network. Observed tooth contact on the testing machine by digital cameras (fig.1) is saved in *.bmp standard or *.jpeg standard. Testing machine it is typical machine as example G513, in which the digital cameras have been mounted. Each camera observes during testing (gears rotate under slightly load) one flank of tooth, it means convex and concave side of tooth. bmp or *. jpeg files are saved in the computer and they are analyzed by special Matlab application, which it is call classifier.

The tooth contact recognition

The tooth contact picture is analyzed by a special program and after its identification ascribed to the proper classes. The practice of tooth contact development allows to differentiate thirteen classes, which are connected with size, shape and position of the tooth contact. Ascribing the tooth contact to the proper 13 classes (table 1) means activation of a suitable correction procedure, which gives proper changes in pinion machine setup. This process can be provided automatically when the cutting machine and the testing machine are CNC machines and they are connected together (by wire) and controlled by a special program. For the conventional machines and even for CNC machines, if it is not accessible a special computer application which automatically changes setup of machines, another program display corrections on the screen and operator realize all changes manually. This program is an external program which resides on the PC computer and most often use the Matlab environment.

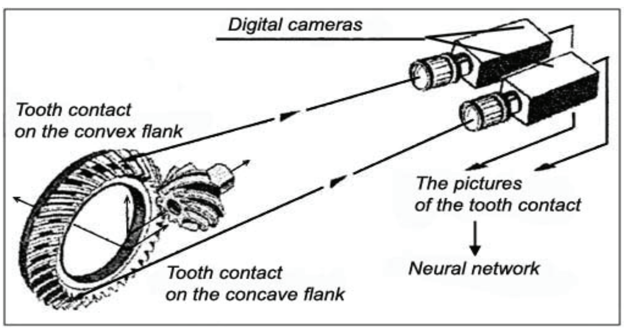


Fig. 1. *An idea of tooth contact recognition*

An observed by the digital camera the tooth contact is not a homogeneous area as a texture and it has not well-defined border lines. This is because the tooth surface is rather as free form surface and consists the ellipses of temporary contacts. Besides, the tooth surface is the result of generation movement of the cutting edges. In each normal section along the tooth, a profile consists of micro-segments, which sizes depend on the feed rate velocity. Pictures of tooth contact which are observed by digital camera are shown on the fig.2a (correct tooth contact) and fig. 2b (too short tooth contact). In both cases it is very difficult to precisely determine the limits (borders) of area of tooth contact. The pictures of tooth contact in *.bmp or *.jpeg formats require standardization before preparation to the features analysis. The standardization is conducted by a special program "standard.m" in Matlab environment and apply to the following:

- changing the picture from RGB to gray scale,
- generating 2-dimensional matrix with linear space vectors with the integer value corresponding to each pixel,
- generating the shape with clear (well-defined) border of the tooth contact.

The differences of non standardized and standardized tooth contact are shown on the fig. 3.

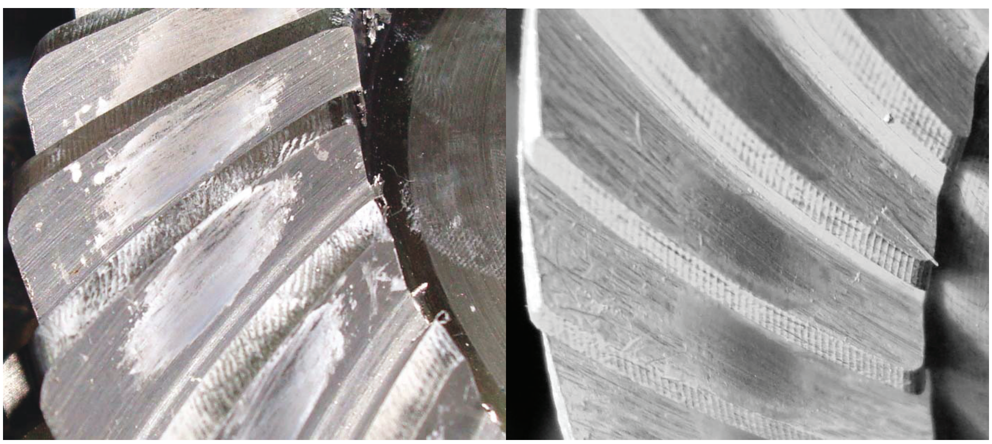


Fig. 2. *Observed by the digital camera tooth contact: correct tooth contact (left), to short tooth contact (right)*

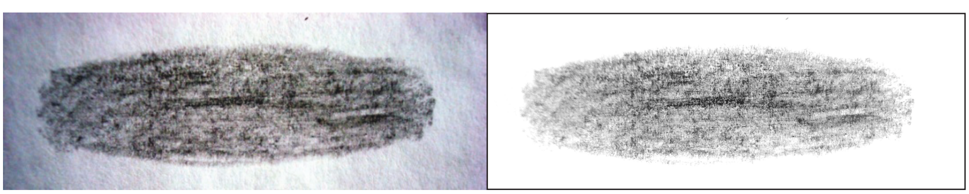


Fig. 3. *The differences between non standardized (left) and standardized picture of the tooth contact (right)*

The features and classes of the tooth contact

Classification to the proper classes depends on the features of tooth bearing (fig.4). The analysis of the features of tooth bearing has been done in Matlab environment. A special procedure "features.m" based on function "regionprops" allows to determine the features of tooth bearing. For the function “regionprops” thirteen (13) features has been chosen. Some of the features are as vectors and therefore in this way the number of features of tooth bearings increase to seventeen (17). The features “Centroid” and “BoundingBox” have together six constituents. In the result, it is examining seventeen (17) features which will identify the tooth bearing. They are:

- Area – scalar – the number of pixel in investigated tooth bearing,
- BoundingBox1,2,3,4 – vector – the smallest polygon included investigated tooth contact,
- ConvexArea – number of pixels in ConvexImage,
- Perimeter – the length in pixels of perimeter of tooth bearing,
- Centroid1,2 – vector, the center of mass of the region,
- MajorAxisLength – scalar - the length in pixels of major axis of ellipse (“a”, fig.1),
- MinorAxisLength – scalar – the length in pixels of minor axis of ellipse, (“b”, fig.1),
- Orientation – scalar – the angle between major axis of ellipse and horizontal axis (“η”, fig.1),
- EquivDiameter – diameter of circle which includes the same numbers of pixels as investigated bearing (“d”, fig.1),
- Solidity – scalar – the relationship between number of pixels in Area to the total number of pixels,
- Eccentrity – scalar –relationship between the distance of ellipse centers (in pixels) to major axis length (in pixels),
- Extent – scalar – relationship number of pixels in tooth contact to number of pixels limited by BoundingBox,
- FilledArea – scalar – number of pixels in tooth contact limited by bounding-Box.

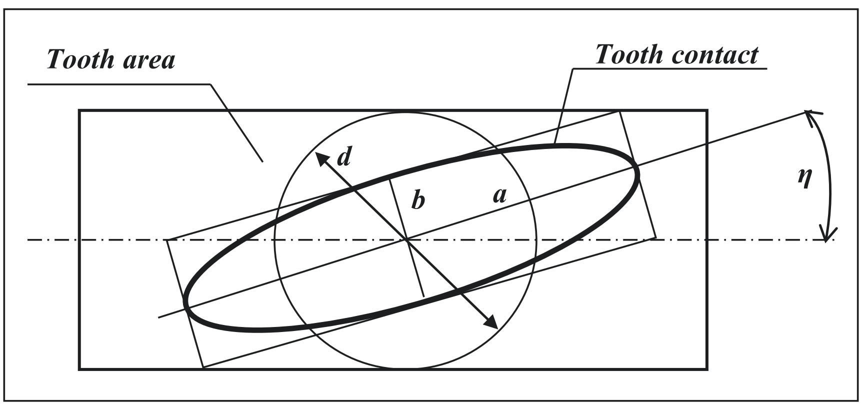
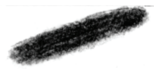


Fig. 4. *The features of the tooth contact*

Table 1. 13 classes of tooth contact

Class of tooth contact	Type of tooth contact	Tooth contact
1	Desired tooth contact	
2	Bias in	
3	Bias out	
4	Short bearing	
5	Long bearing	
6	Wide bearing	
7	Narrow bearing	
8	Toe bearing	
9	Heel bearing	
10	High bearing	
11	Low bearing	
12	Diamond bearing I	
13	Diamond bearing II	

The classifiers of the tooth contact recognition

Approximately two hundred nine (209) different pictures of the tooth contact which belong to thirteen (13) classes (see table 1) have been prepared in order to learn about the neural network. In the initial phases of this experiment the SVM Classifier of Matlab environment has been used. Based on the analysis of many tooth contacts including comparisons of their features, it has been noticed, that some of the features have very closely values, for example: the correct or wide tooth contact had similar number of pixels as the toe or heel bearing. Therefore, the SVM classifier has been identified its by own NBV classifier. During the analysis of many tests for the correlation coefficient equal c=1 it was noticed, that the 2-dimentional set (feature/feature) is very strongly correlated with other several features, for example: the feature number # 12 with # 13 and # 14 and also # 13 with # 14 as shown on (fig. 5). It means, that the features may have similar value and that the tooth contact may be ascribed to the different classes. The correlation factor "c" was decreased to c=0.95 and analysis of the features has been done again (fig. 6). As shown on the fig.6 only the features number # 5 (BoundingBox) and # 13 (Perimeter) are strongly correlated. It is possible to start the next analysis in which the arrangement of vectors in observation space is studied. The arrangement vectors, these are the vectors describing the layout of classes in a function of chosen features. To make such analysis easier and to determine the direction of further studies, it is enough to take 2 features (2-dimensional graph) but the complete analysis include in this case the 13-dimensional space.

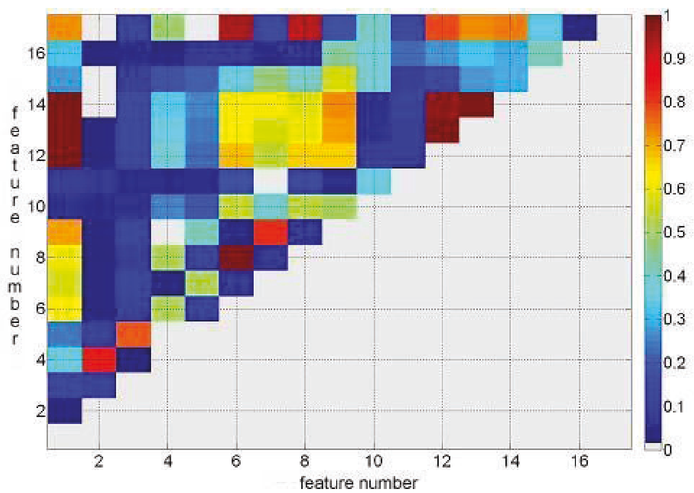


Fig. 5. *Features correlations for the coefficient c=1*

Selection of the features of n-dimensional observation space based on evaluation of the features or group of the features leads to finding subset of the M-features, it is m–dimensional subspace. The subset of the M-features must be subspace which optimizes criteria of the classes' separation. Therefore, it means evaluation of the classes separation based on two criteria: Criterion of Average Scatters (CAS) and Criterion of the Number of Prototypes of classes (CNP). From the number 2N-1combinations of the observation subspace, using criteria CAS and CNP, the best subspace has been chosen which is marked by polygon on the fig.6 – CAS=0.361 and CNP=151. This selected subset of the features of 2-dimensional observation space is shown on the fig.7, it means that the features Centroid1 and BoundingBox3 decide in which class is tooth contact.

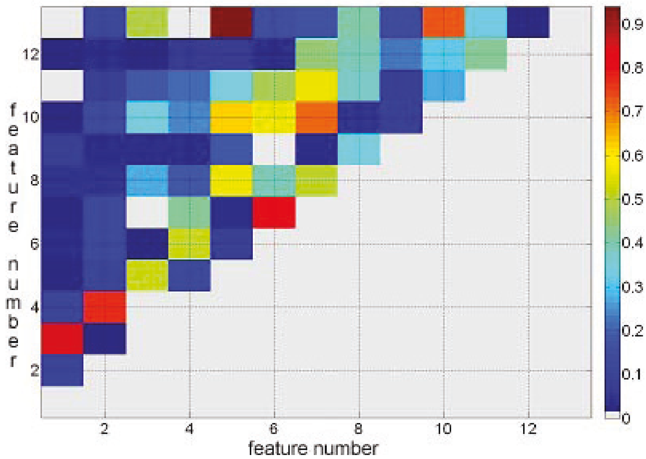


Fig. 6. *Features correlations for the coefficient c=0.95*

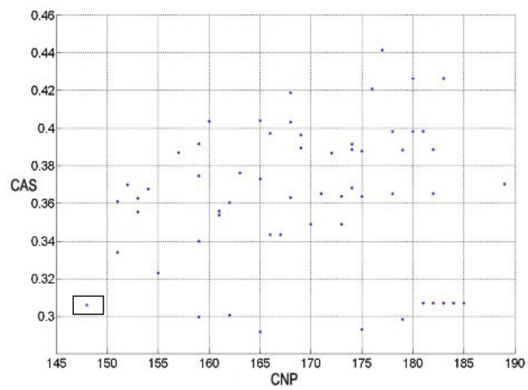


Fig. 7. *Arrangement of the subspace observation for c=0.95 (13 classes)*

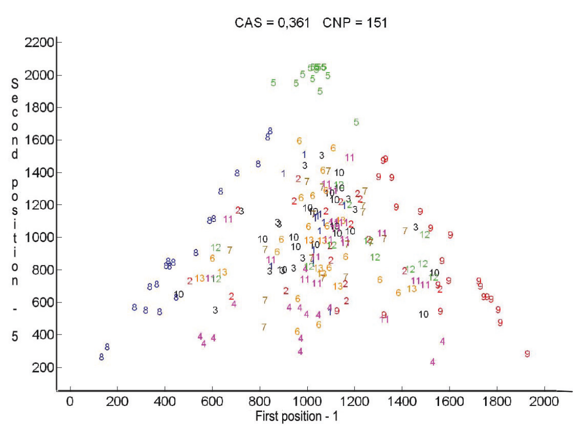


Fig. 8. *Arrangement of the vectors in observation space for the feature 1 and 5 (Centroid1 and BoundingBox3)*

The NBV I classifier

Running the next analyses for the next features is seen, that is no clear group of classes. There is (fig.7) dissipation and confusion of classes. Neural network can recognize two classes but in this task are 13 different tooth contact (13 classes). This problem can be solved based on k-classifiers, it means that should be prepared committee which consists k-classifiers. Thus tooth contact recognition is the multiclass problem. Then is necessary to build the submodels which will be the smaller group of classes. The same set of 13 classes has been divided on the five classes. As criterion of partition were taken prediction direction of the tooth contact movement, similar as technologist make a decision during tooth contact development introducing the I and II order changes.

In the first class numbering all tooth contact are situated centrally and symmetrically with regard to the middle point of tooth surface. Therefore, in the first class are correct and not correct tooth contacts as bias in, bias out, wide, narrow, short and long. The first classifier should be recognized independently to the size and shape of bearing, all tooth contacts are in the middle of tooth, toe bearing, heel bearing, low and high bearing.

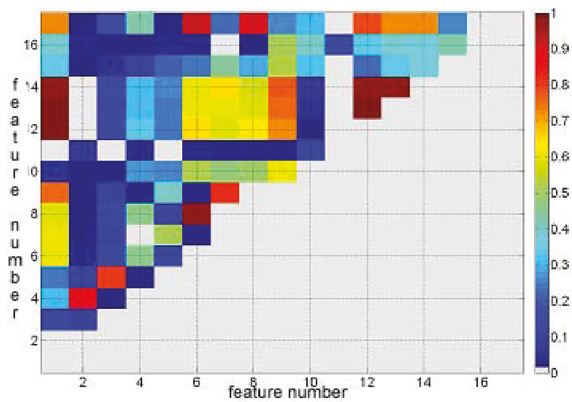


Fig. 9. Features correlations for the coefficient c=1 for the seventeen features (5 classes)

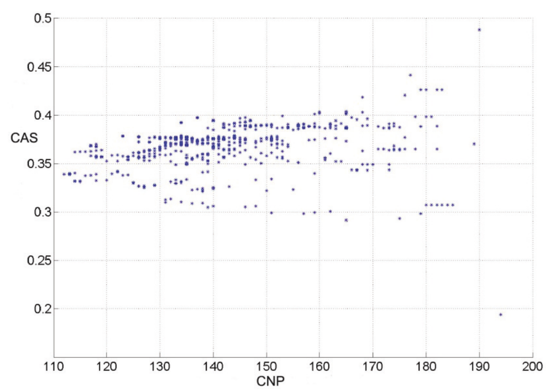


Fig. 10. Arrangement of the subspace observation for c=1 (5 classes)

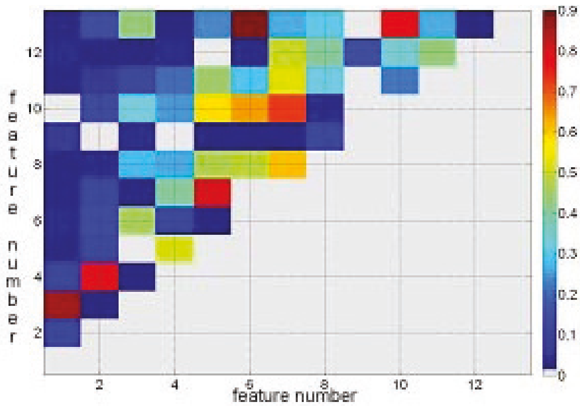


Fig. 11. *Features correlations for the coefficient c=0.9 for the seventeen features (5 classes)*

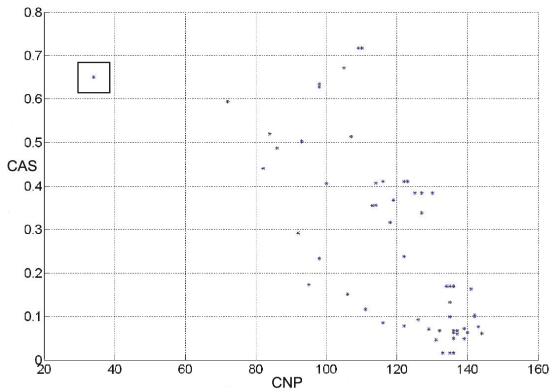


Fig. 12. *Arrangement of the subspace observation for c=0.9 (5 classes)*

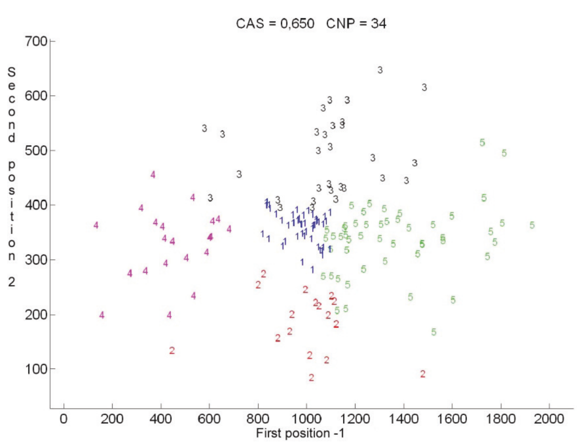


Fig. 13. *Arrangement of the vectors in observation space for the First NBV classifier (5 classes)*

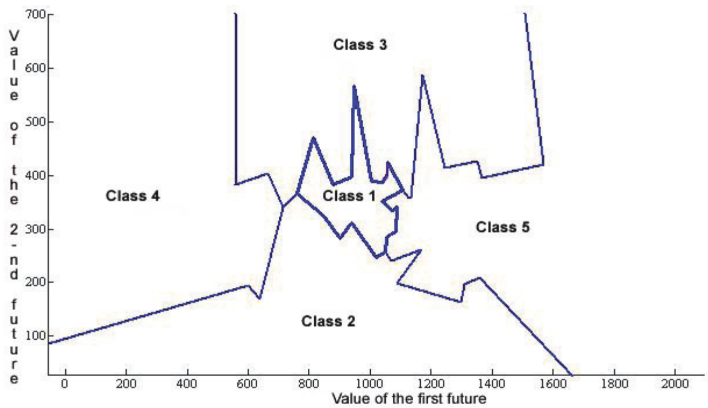


Fig. 14. *An illustration of I Classifier for five classes*

The NBV II classifier

Studying correlation of the features for coefficient c=1 of all 17 features for less numbers of classes (5 classes) still a very strong correlation between ConvexArea, FilledArea and EquivDiameter (fig.8) have been noticed. Such strong correlation influences arrangement of vectors in the observation space (fig.9) where criteria CNP and CAS are not satisfied. Similarly as before this correlation of the features for coefficient c=0.9 (fig.10) and arrangement of subspace observation (fig.11) have been verified. The best subspace of the observation subspace marked by polygon (fig.11) where CAS=0.65 (Criterion of Average Scatters) and CNP=34 (Criterion of the Number of Prototypes) has been chosen. The selected subset of features 2-dimensional observation space is shown on the fig.12, it means that features Centroid1 and Centroid2 decide in which class the tooth contact is located.

On the fig.12 the well-defined group of classes is seen. It is possible to determine the clear borders between the classes. Continuing such classification problem is necessary in order to define the next classifier which will recognize the next five classes. Second classifier should recognize: correct tooth contact (class 1), wide tooth contact (class 2), narrow tooth contact (class 3), short tooth contact (class 4) and long tooth contact (class 5). This classifier will recognize tooth contacts which are in the central area of the tooth flank. Certainly, II NBV classifier is based on the same features as I NBV classifier. Taking the same correlation factor as before for the I NBV classifier (c=0.9), the observation subspaces criteria have been analyzed. This criterion CAS has maximum value and criterion CNP has minimum value. Subspace marked by polygon has advantageous values: CAS=0.762 and CNP=15 (fig.13). For this observation subspace a graph have been made which illustrates arrangement of vectors in the observation space (fig. 14).

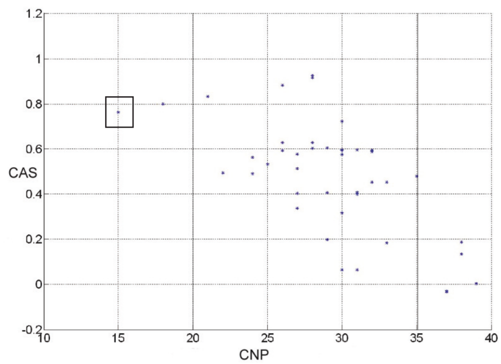


Fig. 15. Arrangement of the subspace observation for c=0.9 (5 classes)

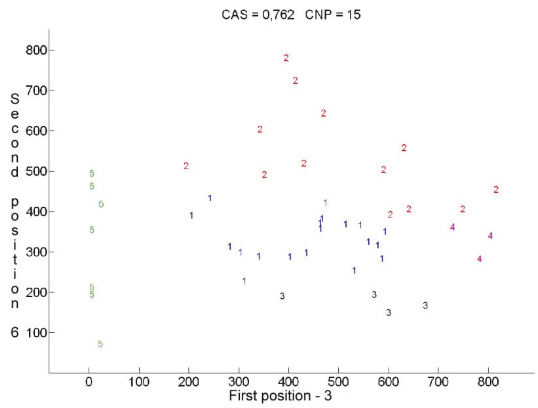


Fig. 16. Arrangement of the vectors in observation space for the Second NBV classifier (5 classes)

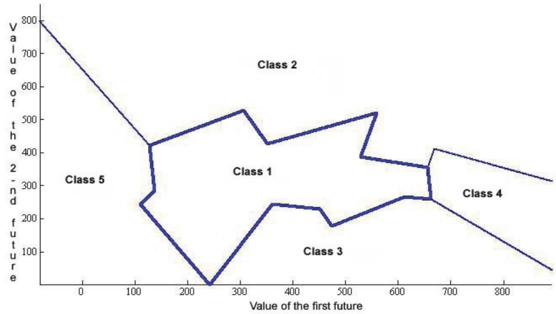


Fig. 17. An illustration of II Classifier for five classes

Fig. 12 shows a well-defined group of classes. It is possible to determine the clear borders between the classes. Running classification problem is necessary in order to define the next classifier which will recognize next three classes. The next classifier number III NBV will recognize: correct tooth contact (class 1), bias in (class 2) and bias out (class 3). Activity of third classifier focuses on the tooth contact which is in the middle of tooth flank however it has correct length, width and bias out or bias in. Similarly as in I and II, the classifier NBV, is analyzed by the same 17 features. An arrangement of subspace observation is shown on the fig.15. The subspace which is marked by polygon has advantageous values according to CAS and CNP criteria: CAS=1.39 and CNP=3. An arrangement of vectors in the observation space for the Third NBV classifier (3 classes) shows well-defined group of classes. The two dimensional graph of the arrangement of vectors in the observation space for features Orientation and Extent illustrates clear divided areas of classes (fig. 16).

The NBV III classifier

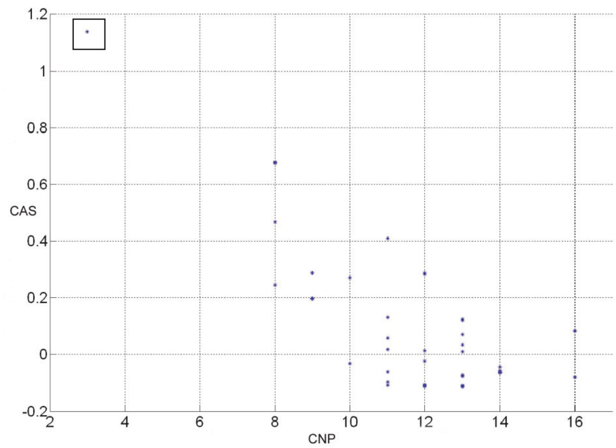


Fig. 18. *Arrangement of the subspace observation for c=0.9 (3 classes)*

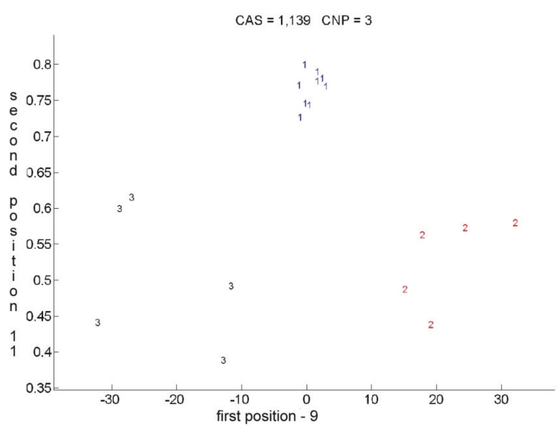


Fig. 19. *Arrangement of the vectors in observation space for the Second NBV classifier (5 classes)*

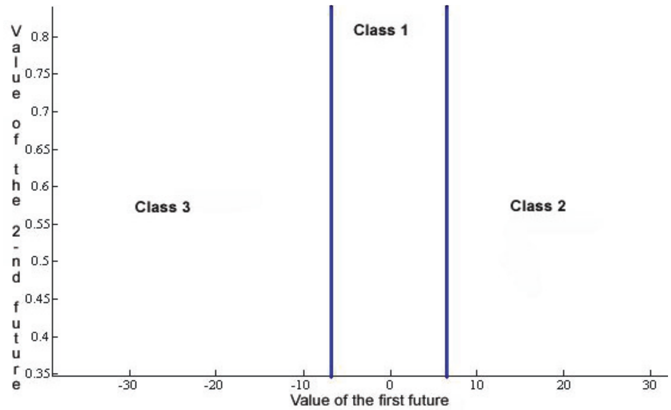


Fig. 20. *An illustration of III classifier for three classes*

Conclusions

Verification of classifiers has been done accepting the same conditions as in production of the spiral bevel gears. Taking the tooth contact as a short and in the heel position, I NBV classifier identifies it according to the principle of recognizing to the fifth (5) classes. After applying of II order changes (increasing the eccentric angle and cradle angle) and cutting the pinion, the tooth contact was in the middle of tooth but moved down toward the dedendum. For this tooth contact the I order change has been used meaning the head setting was increased. After the finally cutting, the tooth contact was in the middle of tooth and it had correct size and shape (ellipse). It means, that all three "classifiers are correct and they satisfied requirements of the technologist.

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