Chapter 4

Fuzzy Logic Applications in Metrology Processes

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Additional information is available at the end of the chapter

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Abstract

Three-dimensional metrology is concerned with checking the conformity of machined parts with the geometrical specifications on their definition drawings from the design office. Three-dimensional measurement is a firmly established technique in the industry. For this, we apply the fuzzy logic to solve probing. Probing technology is widely used in three-dimensional metrology. In addition, we measure the very small dimensions, that is, the measurement at the micrometer scales. This chapter presents a new approach to the developing gear curve (CMMs). This method aims to select the most likely contact point for each successive arc by applying geometrical criteria and a fuzzy logic estimator, as you know there are several methods, but the fuzzy logic is more efficient and closer to the profile reel. The fuzzy logic system is particularly suitable for application to the three-dimensional metrology, including applications on a small radius probe as well as probing discontinuities to the flank profile. In addition, the time allowed is 144.09 s. Tests were carried out on gearboxes of agricultural machinery in the factory of my country (Algerian Tractors Company).

Keywords: metrology, fuzzy logic, gears, model gears, probe, path

1. Introduction

Coordinate measuring machines (CMMs) are becoming increasingly important in measurements and the verification of the dimensional quality of manufactured parts and products. First, today's gear inspection is a description of the nominal geometry of the gear teeth, which are limited some flank profile traces. The new principle of the corrected determination of the measured point in the metrology of coordinates is brought to the system of the fuzzy logic. This means that for the measurement with great accuracy of a complex surface's mechanical part, we propose a new algorithm for the compensation of the tip of the radius of the stylus in a process of scanning by three-dimensional coordinate CMMs. The proposed algorithm is dedicated to high-definition measurement. Advantages of the algorithm are that we do not calculate the normal vector and we do not use a Non-uniform rational basis spline (NURBS) is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces. It offers great flexibility and precision for handling both analytic and modeled shapes. In general, editing NURBS curves and surfaces is highly intuitive and predictable. Control points are always either connected directly to the curve / surface, or act as if they were connected by a rubber band [1]. The method is based on the fuzzy logic algorithm, which is a well-known method to approximate the ideal position that minimizes the sum of the squared residual errors between the clearance and the model. This choice is motivated by the robustness of this method and it is important to underline here that no attempt to implement it within the coordinate measuring machine (CMMs) software has been reported in the three-dimensional metrology literature. Digital applications have dealt with the case of a gear tooth gear that is fitted to the gearbox of machine tools. The comparison between the real surface obtained by the three-dimensional measuring machine and the ideal model that gives us defects of shape of the tooth. But this precision is generally obtained only for the measurement of well-known shapes of the piece measured and when its dimensions greatly exceed the radius of the tip of the probe, and for this reason, the algorithm is used for the correction of the radius of the probe. For example, simple surfaces form profiles that are not geometric primitive sections known as planes (circle, sphere, cone, gear, etc.).

2. Fuzzy logic applications in metrology processes

Metrology engineering has employed fuzzy logic in the detection of the defect of gears with straight cylindrical teeth. It has also been applied to process control, the modeling of the developing profile of a tooth circle, its optimizations, looks for defects in shape, and position.

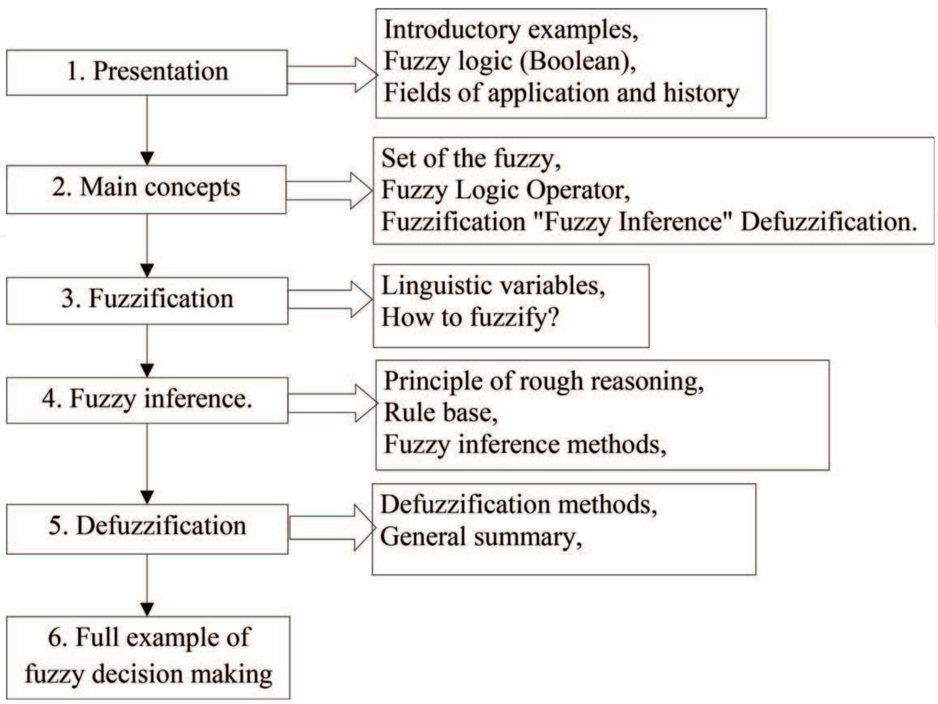

Figure 1. Synoptic of fuzzy logic.

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In this research, we investigate these applications in more detail. See the synoptic of fuzzy logic in **Figure 1**.

3. Geometry and the specification of spur gear with the module

Pressure angle remains the same throughout the operation, and the teeth are weaker. It is easier to manufacture due to its convex surface. The velocity is not affected due to the variation in the central distance. Interference takes place; there is more wear and tear as contact takes place between convex surfaces (**Figure 2**).

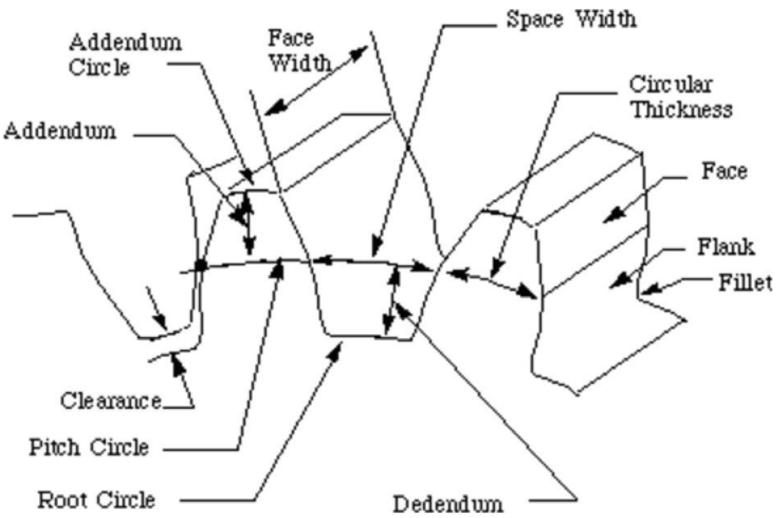

Figure 2. Involute profile.

4. The implementation of fuzzy logic systems

4.1. Problem of probing the tooth

Firstly, the probing obstacle is in zones 1 and 2 when the information is entered by the tridimensional measuring machine (see **Figure 3**). Indeed, we saw that the segment (ab) is undefined after having transferred the coordinates of the center of the ball. That is, there are no coordinates for probing this one (**Figure 3-1**), and the same goes for zone 2; when we did the transfer, no results were interpreted because the segment (ab) is unknown. To solve this problem of probing, we apply the system and notions of fuzzy logic.

4.2. The principle of determination of the measured point corrected

As regards the measurement with high accuracy on CMMs, we specify the probe path. For this, we propose a new algorithm for the compensation of the radius of the tip of the stylus in a process of scanning the surface of the tooth by CMMs. The proposed algorithm is dedicated to the measurement of high definition. It is done to calculate the normal vector.

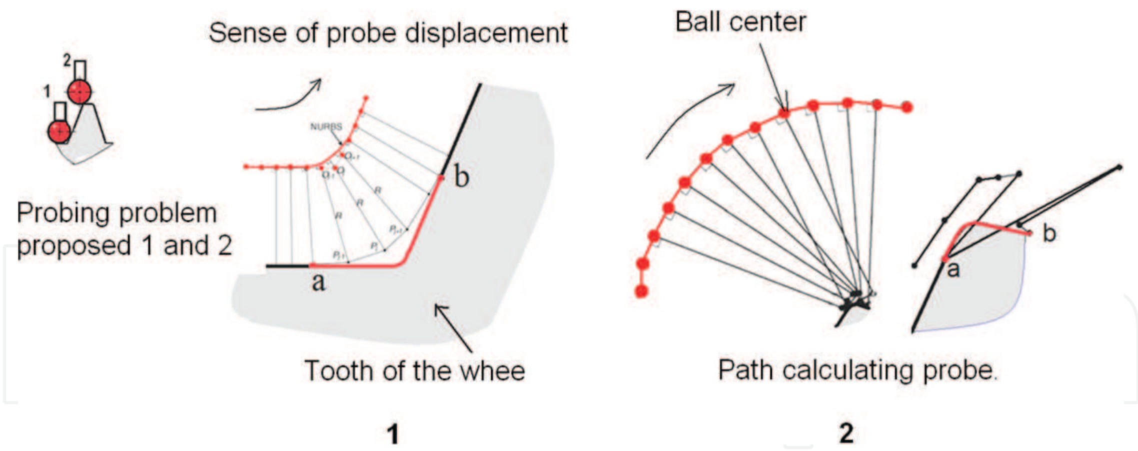

Figure 3. Problem of probing the tooth of a wheel.

The proposed compensation method consists of the following steps [1]:

- realization of a series of high-density measurements on the characteristic of geometry measured by the spherical stylus tip,
- contour of the sample defines a bow per ball, for each measured point,
- calculating the points of intersection A_i and A_{i+1} for each arc, with the next and the previous point,
- for each arc, the estimate of the point of contact with S_i as the characteristic of this point is located in the middle of the arc,
- determination of angular compensation using the fuzzy logic knowledge base and the application of compensation based on the corresponding angular adjustment.

The calculation of angles $\Delta\alpha_i$ can be achieved by exploiting a known basic variety or other-rule artificial intelligence techniques [2, 3]. In the experimental implementation of this method, we opted for the calculation of the angles $\Delta\alpha_i$ with a fuzzy logic algorithm [4].

4.3. Analysis of the geometry of the probe trajectory

We consider point O_i as one of the data points describing the position of the center of the ball of the spherical stylus registered by the CMMs (see **Figure 4**) [5]. We take the previous additional points O_{i-1} and the following point O_{i+1}. Considering the external envelope tip of the stylus at the O_i point, it can be said that the ball of the stylus is always in contact with the material of the gears and that no part can be at the limit of the tip of the stylus; the point of contact of the stylus ball with the measuring surface is on the arc A_iA_{i+1}. The points A_i and A_{i+1} have points of intersection of the three circles that have the centers O_i, O_{i-1} and O_{i+1}, respectively [6].

All three circles have a radius R equal to the radius of the stylus ball, with which the preliminary calculations of the CMMs are made, according to the qualification of the probe system. All points of the arc are selected to transfer the corrected measured points associated with the

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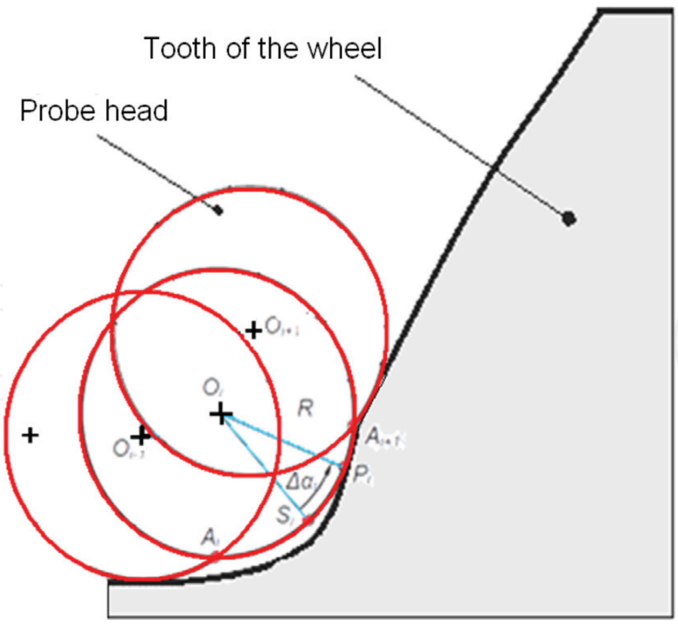

Figure 4. Analyzes the geometry of the sweep path for the determination of the measured point corrected.

measured points O_i. However, as a first approximation, the ideal points of the stylus ball in contact with the measuring surface are evaluated midway on the arc: A_iA_{i+1}. Indeed, some adjustments of the corrected measured point may be essential.

In the first estimate, a preliminary point S_i was chosen to the bow $A_iA_{i+1.}$ Then, we take into account the mutual position of the neighboring points, O_i and $O_{i-m}, \ldots, O_{i-1}$ and $O_{i+1}, \ldots O_{i+n}$. (where m and n are a number of previous and following points, respectively). An angular adjustment $\Delta\alpha_i$ is obtained to improve the new position of the ideal point of contact with the flank and the ball and thus correctly calculate the points which are the closest P_i. Calculations of $\Delta\alpha_i$ can rely on artificial intelligence techniques that are based on the rules of fuzzy logic. In the experimental implementation, we use the method of correction the measurement of the points of stylus (stylus tip envelop method). We opted for a fuzzy logic algorithm to compute $\Delta\alpha_i$. The entry of this system of logic is summarized in **Table 2** with two components: $\Delta\alpha_i$, Az_i, and Δk_i. We define the first magnitude Δz_i which is the distance between point O_i and the point of intersection with the line $(O_{i-1}O_{i+1})$. The second component, Δk_i, is the distance between point O_i and the point of intersection with the line $(O_{i-1}\ O_{i-2})$. These elements define the input values and output (see **Figure 4**).

4.3.1. Inputs

The choice of input and output variables depends on the control we want to achieve and the available parameters. In our chapter, we can consider the entries x_m and y_m which are the Cartesian coordinates of the points entered by the three-dimensional measuring machine in the course of scanning the surface of the right or left flank by the probing system. This choice is intuitive and based on the experience of the operator.

4.3.2. Output

The outputs are based on the problem that was posed; anyway, we can find one or more outputs and so on. Finally, it is lucid that the outputs in our work are two: x_m and y_m.

4.3.3. Fuzzification

First, we proposed the parameters in our tests on the CMMs, which are within the Metrology Laboratory of ENP-Oran (see **Table 1**). These are very important for simulation calculations.

	Minimum value	Maximum value
t (s)	—	250
θ (radian)	0.2	30
x_m (mm)	—	26
y_m (mm)	—	26
i	100	200
Δk_i	—	200
Δz_i	—	200
α_i	—	200

Table 1. Parameters of the test.

So this step allowed us to give the different linguistic variables that will be used during the gear control by the fuzzy logic [7–15].

4.3.4. Rule base (inference)

Indeed, we exploit **Table 2** to build the inference of fuzzy logic in C; however, we do not have to complete all the boxes. The rules are developed by an expert and his knowledge of the problem [12, 13, 15].

$$\textit{IF conditions}\ldots.\textit{THEN action}$$

$$\textit{IFconditions}\ldots\textit{THEN action} \tag{1}$$

4.4. Construction of fuzzy logic matrix

The matrix is in the form of **Table 2** or a matrix that we can build according to the previous parameters, Δk_i, $\Delta \alpha_r$, and Δz_i, while the purpose of this table is to know which elements are most influenced during the implementation of fuzzy logic to spur gears.

		Δk_i				
	$\Delta\alpha_r$	Very min	Min	Zero	Max	Very max
Δz_i	Very min					
	Min		Min			
	Zero			Zero		
	Max				Max	
	Very max					

Table 2. Matrix of fuzzy logic.

N.B: After completing the logic matrix of **Table 2**, it was concluded that the factors that influenced on the logic estimator are:

$$Matrix = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (2)$$

5. Probing and data processing

Over the last 20 years, remarkable progress has been made in three-dimensional measurement technology with regard to the mechanical elements of the machine, control equipment, and software.

6. Instruments for measuring capacity

The accuracy of the probe during scanning is generally several tens of micrometers, but this accuracy is generally not achieved for the measurement of well-known shapes as well as when the size of the part greatly exceeds the radius of the feeler ball because of the algorithms used for the sharp radius of correction stylets.

For example, spline profiles that do not compose a part of a geometric primitive known as (circle, sphere, cone, torus, etc.), they present particular difficulties to establish the method of the normal vector. Left surfaces are now very common (car, bodies, consumer products of ergonomic shapes, turbine blades, etc.).

In addition, small features become commonplace and, although measurements are made by digitization, the correction can result in the introduction of unacceptable errors [16–18].

7. Measures the coordinates of tooth profile points by the three-dimensional measuring machine (CMM)

In fact, this semi-experimental part is very important for applying these notions of fuzzy logic to the contour of the flank of the left or right tooth. However, we are able to bring back information through a known mathematical model or by asking a laboratory to provide it to us. In short, the result of the processing of information is the same, either by borrowing the mathematical model or by directly probing by CMM (see **Figures 4–6**) [8, 11].

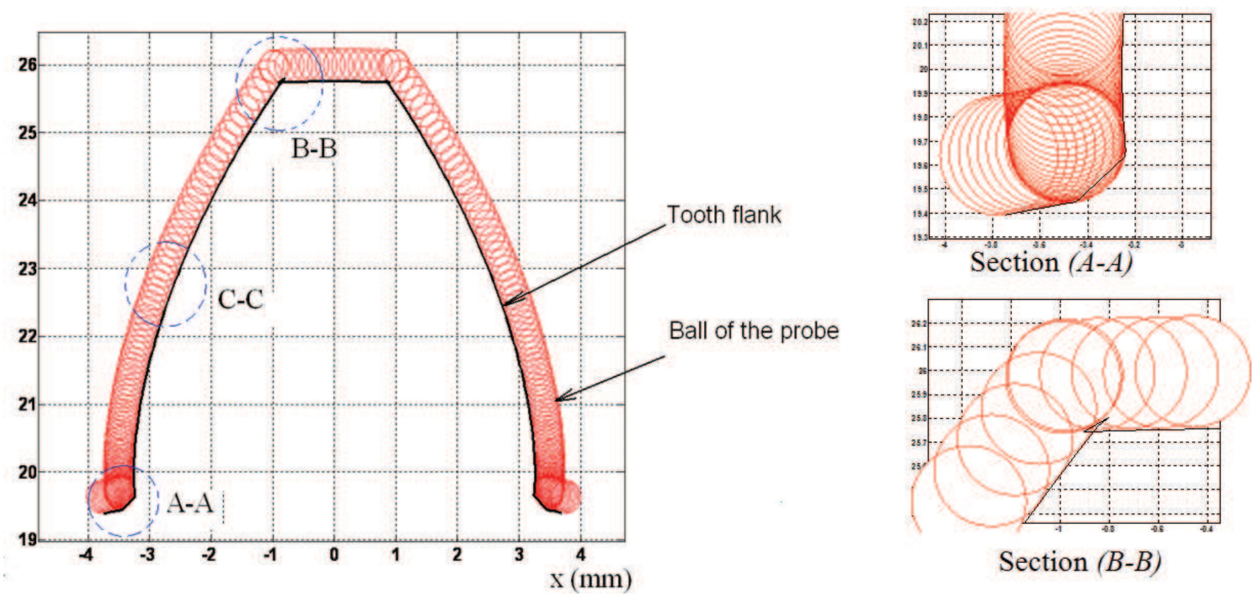

Figure 5. Mathematical model: sections (A-A), (B-B) and (C-C).

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8. Presentation of the algorithm

The presentation of the fuzzy logic algorithm has been introduced (see **Figure 6**); this logic affects one or more steps of the algorithm to try to increase its performance including accuracy and speed, and there are several variables. Some of these variables expand, and the abbreviation of the corresponding iterative point asserts that it would be a good response to the algorithm. To make an algorithm choice, there are several criteria that must be checked:

- speed,
- precision,

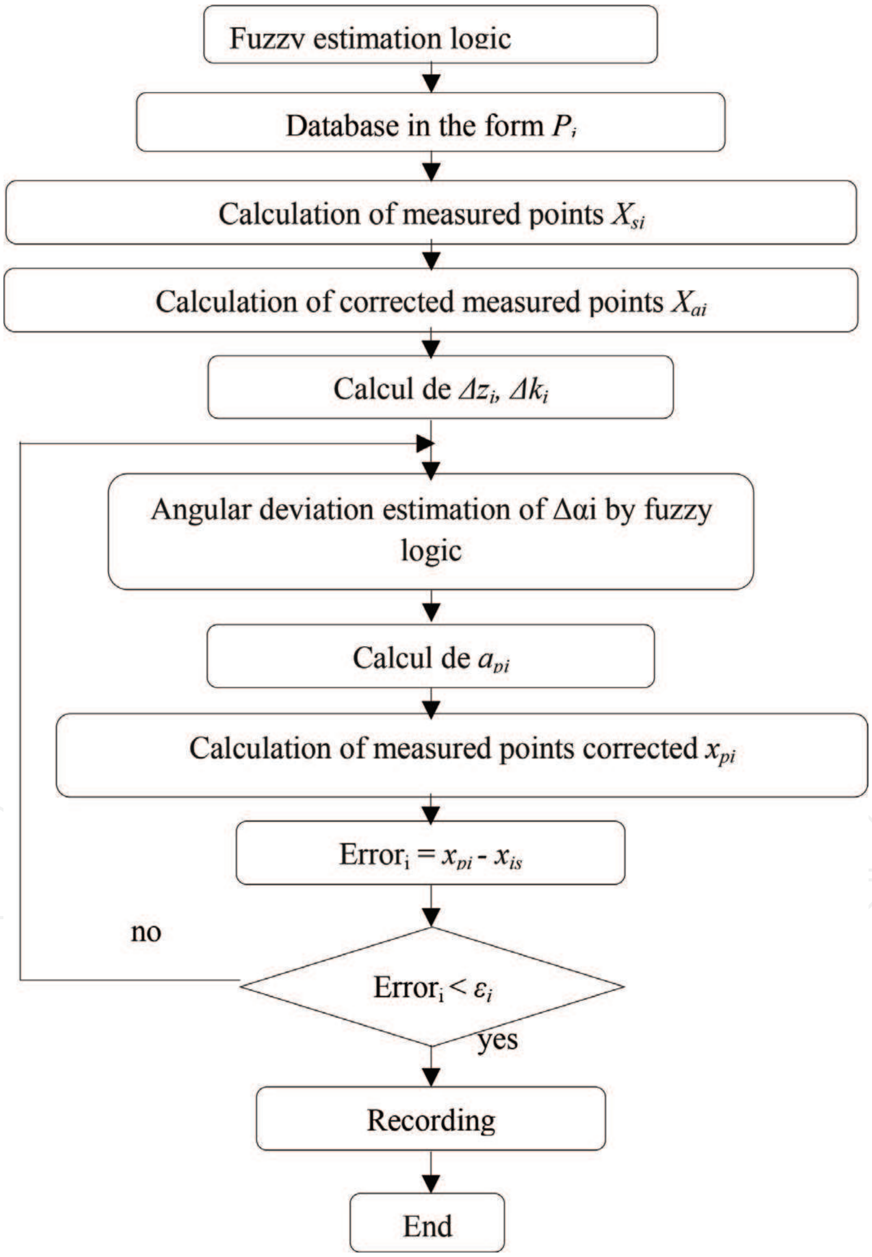

Figure 6. Flowchart of fuzzy estimator logic.

- stability,
- robustness and simplicity.

The importance of any of these four criteria depends on the application of the final program. The development of a complete system of the quality inspection of the manufactured parts requires the coordination of a set of processes to acquire data, its dimensional evaluations, and comparisons with the proposed reference model. For this, it is essential to make certain conceptual knowledge profitable not only for the object to be analyzed but also for the environment. In this case, the goal of this chapter is to establish a procedure for automating the modeling of the surface inspection of complex parts such as gears. Allowing to correct the relative differences of the manufacturing parameters, then, the adopted criteria includes fast convergence, the robustness of the system, and the simplicity of the interface. Finally, the new algorithm is summarized by the diagram of the following flowchart [2]:

9. Calculation of the corrected measured points

We used the following equations to achieve these results (see **Figure 7**). Equation of right which is between the points P_{i+1}, P_{i-1}:

$$y_i = a_i x_i + b_i \tag{3}$$

The equation of the line that passes through the point Pi and perpendicular to the line that passes through the points ($P_{i+1}P_{i-1}$):

$$y_i = c_i.x_i + d_i \tag{4}$$

The equation between two points P_{i-1}, P_{i-2}:

$$y_i = e_i x_i + f_i \tag{5}$$

The equation of the line that passes through the point P_i and perpendicular to the line ($P_{i-1}P_{i-2}$):

$$y_i = m_i x_i + n_i \tag{6}$$

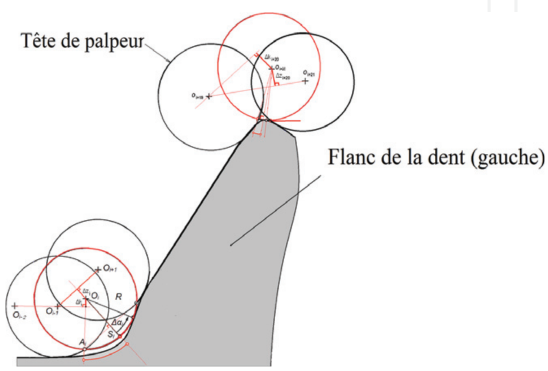

Figure 7. Determination of Ak_i, $\Delta\alpha_i$, Az_i (sections *B-Band C-C*).

We take theoretically the tolerance values for each point gained in the range (*0.0001*.rd).

Equation of the circle includes

$$(x - x_i)^2 + (y - y_i)^2 = r^2 \tag{7}$$

(see **Figure 7**)

r is the radius of the probe sphere (r = 0.2–5 mm).

We have determined the following values a_i, b_i, c_i, d_i, Δ_i.

$$\begin{cases} a_i = \dfrac{y_{i+1} - y_{i-1}}{x_{i+1} - x_{i-1}} \\ b_i = y_{i-1} - \dfrac{y_{i+1} - y_{i-1}}{x_{i+1} - x_{i-1}}.x_{i-1} \\ c_i = -1/a_i \\ d_i = y_i - c_i.x_i \\ e_i = \dfrac{y_{i-1} - y_{i-2}}{x_{i-1} - x_{i-2}} \\ f_i = y_{i-1} - e_i.x_{i-1} \\ m_i = -1/e_i \\ n_i = y_i - m_i.x_i \end{cases} \tag{8}$$

$$\Delta_i = (2.d_i.c_i - 2.y_i.c_i - 2.x_i)^2 + 4.\left(x_i^2 + (d_i - y_i)^2 + r^2\right)(c_i + 1) \tag{9}$$

We can take the numbers that vary between i = 1 and 200 points.

N.B: We took into consideration the rest time of the 0.25 s machine. We calculate the Cartesian coordinates X_{si} (x_{si}, y_{si}):

$$\begin{cases} x_{si} = \dfrac{-(2.d_i.c_i - 2.c_i.y_i - 2.x_i) \pm \sqrt{\Delta_i}}{2(c_i + 1)} \\ \text{et} \\ y_{si} = c_i.x_i + d_i \end{cases} \tag{10}$$

(see **Figures 8** and **9**)

We can calculate the coordinates of the points X_{ai} (x_{ai}, y_{ai}):

$$\begin{cases} x_{ai} = \dfrac{x_i + x_{i-1}}{2} \pm a_{oi}.\dfrac{\sqrt{4.r^2 - (x_i - x_{i-1})^2 - (y_i - y_{i-1})^2}}{2\sqrt{a_{oi} + 1}} \\ \text{et} \\ y_{ai} = \dfrac{y_i + y_{i-1}}{2} \pm a_{oi}.\dfrac{\sqrt{4.r^2 - (x_i - x_{i-1})^2 - (y_i - y_{i-1})^2}}{2\sqrt{a_{oi} + 1}} \end{cases} \tag{11}$$

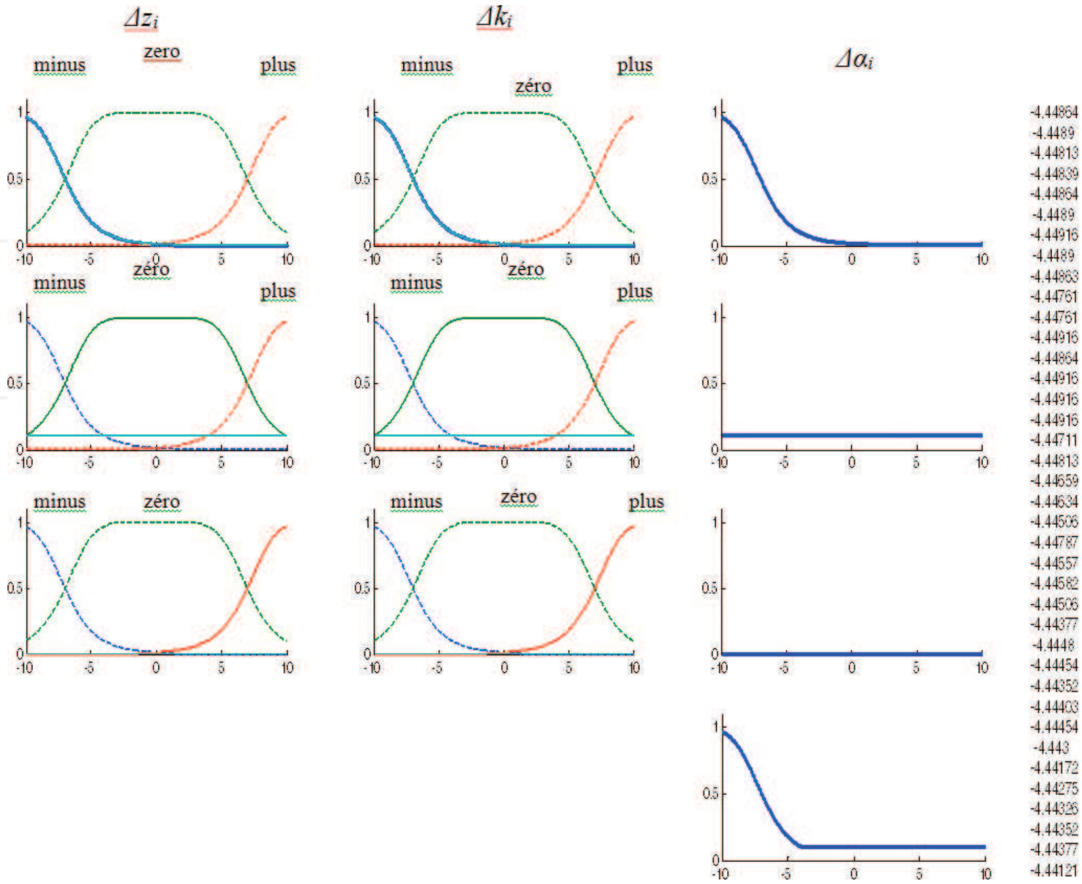

Figure 8. Screen printing of Δz_i, Δk_i, defuzzification, $\Delta \alpha_i$ conclusions according to Mamdani rules [6, 15].

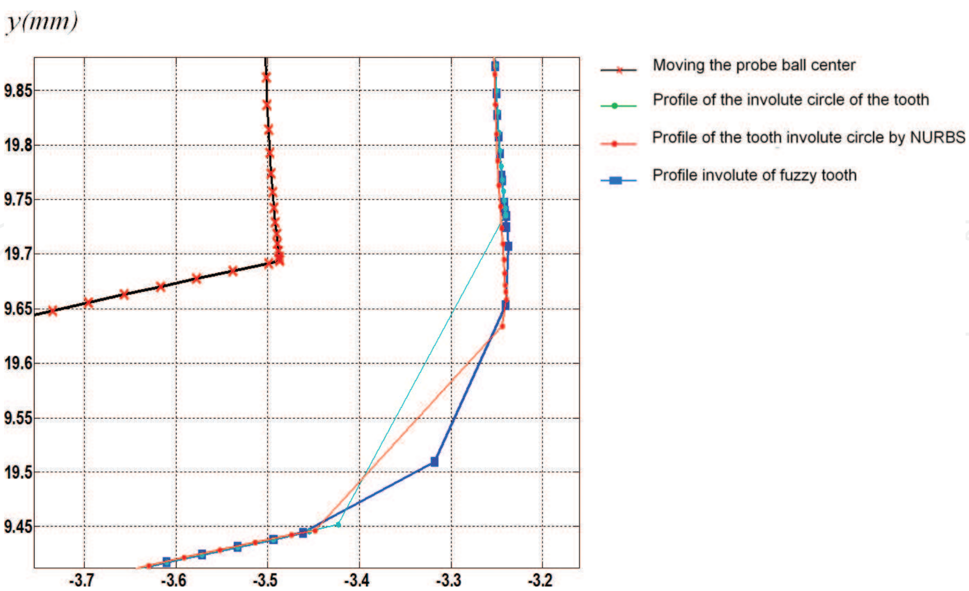

Figure 9. Section *A-A*.

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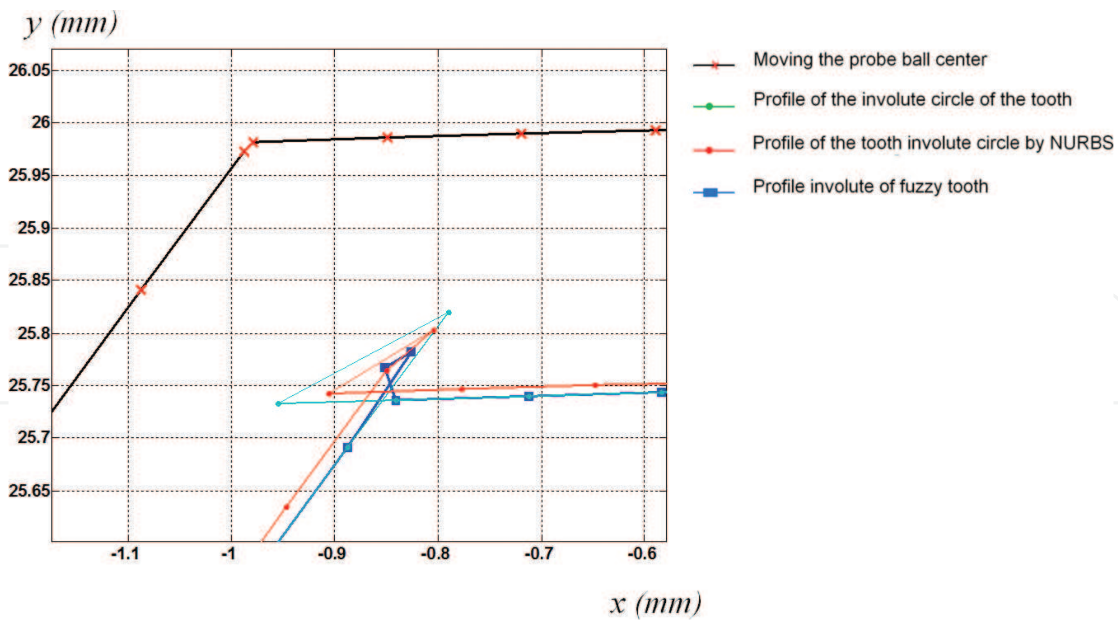

Figure 10. Section *B-B*.

Then, the values Δz_i, Δk_i are:

$$\begin{cases} \Delta z_i = \sqrt{\left(\left(\frac{d_i - b_i}{a_i - c_i} - x_i\right)^2 + \left(a_i\left(\frac{d_i - b_i}{a_i - c_i} + b_i - y_i\right)\right)^2\right.} \\ \text{et} \\ \Delta k_i = \sqrt{\left(\left(\frac{n_i - f_i}{e_i - m_i} - x_i\right)^2 + \left(e_i\left(\frac{n_i - b_i}{e_i - m_i} + f_i - y_i\right)\right)^2\right.} \end{cases} \tag{12}$$

(see **Figures 8–10**)

According to the graphs of fuzzy logic, we can conclude the values of $\Delta\alpha_i$ (see **Figure 8**). We calculated Δz_i and Δk_i using the formula of the above relation (13) to calculate these quantities; we determine the values $\Delta\alpha_i$ using fuzzy logic, *max-min* inference, and the generalized function bell and then defuzzification by the centroid method [18] (see **Figure 10**).

In our work, we use the generalized bell shape:

$$y_i = \frac{1}{\left(1 + \left(\left((x_i + 14)/7\right)^3\right)^2\right)} \tag{13}$$

where z (r) and k (r) represent the values of the linguistic variables of the deviations Δz_i and Δk_i. From these, we deduce the angular difference $\Delta\alpha_i$. **Figure 8** shows an impression of the screen language values define for each input value.

10. Comparison of different sections at the level of the tooth

10.1. Section *A-A*

After applying the fuzzy logic and plotting the tooth curve, we notice that the green curve is far from the ideal curve; this is the normal vector method. But blue tracing is closer to this one because of having dots that define the involute curve, the red curve is closer to the curve of fuzzy logic (see **Figure 9**).

10.2. Section *B-B*

In that case, we find that the intersection between the involute curve and the outer circle gives a large deviation as expected. In addition, this leads to an increase in errors, that is, the increase in the gap (see **Figure 10**).

For example, if we determine the height of the tooth by the formula h = $h_a + h_f + \Delta e$ (see **Figure 10**), then the percentage of the error according to the definition can be calculated as follows:

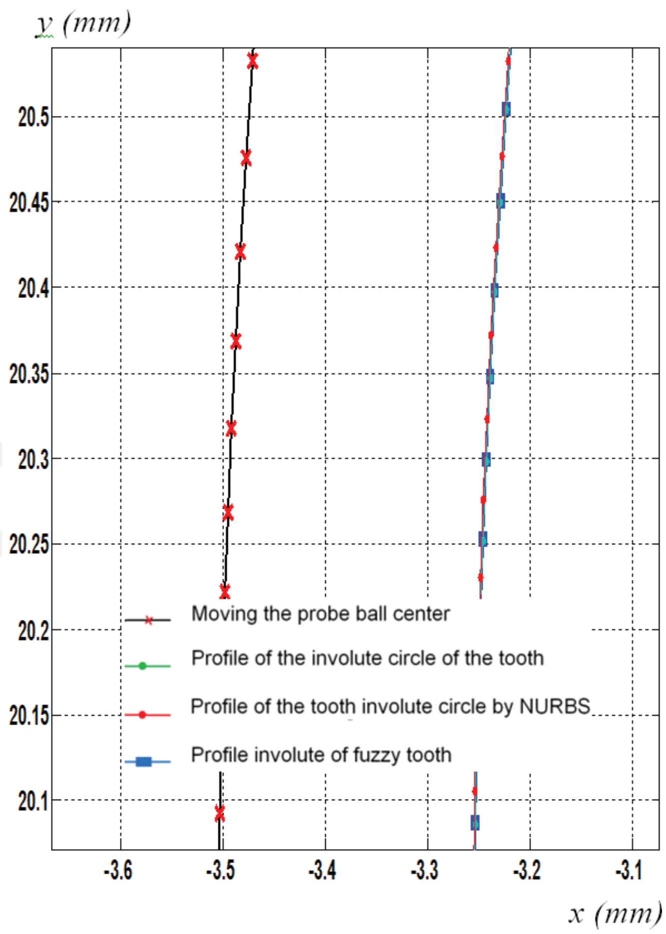

Figure 11. Section *C-C*.

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$$\Delta e_f = f_1 - f_2 = 25,77–25,72$$

$$\Delta e_f = 0.05 \text{ mm}$$

$$\Delta e_f\% = 8.33$$

$$\Delta e_g = g_1 - g_2 = 25,82–25,72$$

$$\Delta e_g = 0.15 \text{ mm}$$

$$\Delta e_g\% = 25$$

So, it is intolerable to accept miscalculations of more than Δe_g % = 25 by the normal vector method, so the piece was rejected. On the other hand, if we use the same database, we find errors of fuzzy logic for this piece: Δe_f % = 8.33 mm, while the piece was accepted. It was concluded that the fuzzy logic method is closer to the ideal measurement.

10.3. Section *C-C*

In this case, there is no difference between the two methods (fuzzy logic and the normal vector), the error is zero. However, the method *FL* does not influence the measurement of spur gears (see **Figures 11** and **12**).

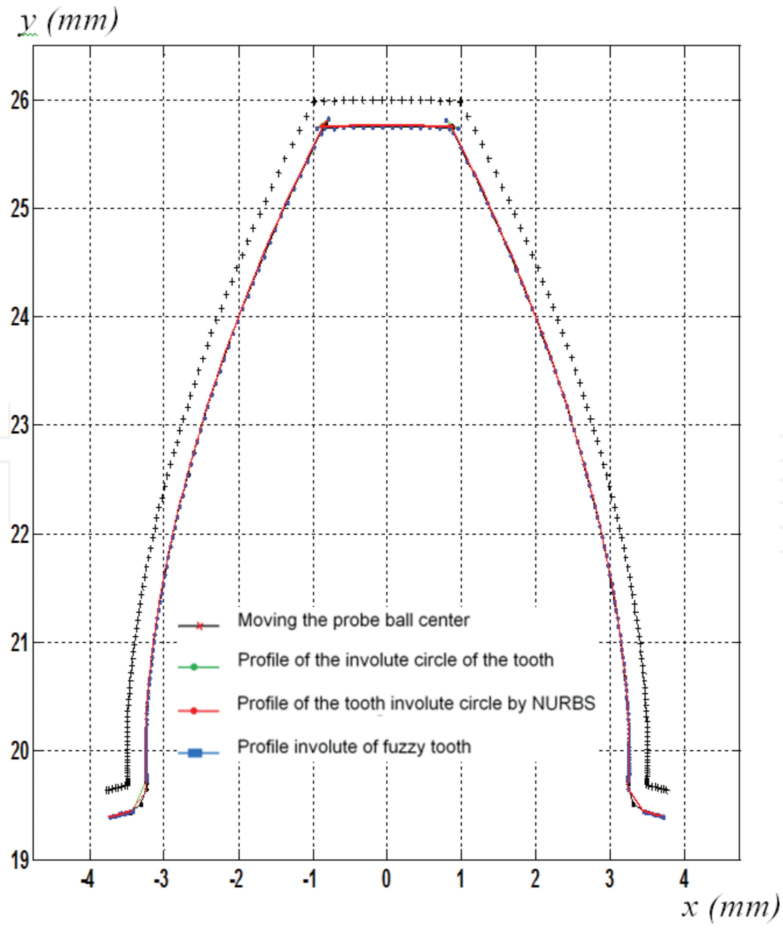

Figure 12. Combination of the x and y coordinates by forming the tooth.

11. Calculation of profile error obtained by the fuzzy logic method

Concluding that the proposed method presents the maximum error in curve peaks, among its values are 0.15, 0.14, 0.1, and 0.1 mm. These peaks have been found to represent intersections between two curves. The weakness of this method is in the intersections of the curves. But in the journey with himself, he does not have any difference.

Indeed, it has been deduced that the result of fuzzy logic is the closest to the ideal curve because of some points that appeared to define the involute curve; at this moment; we could not calculate them by the normal vector method. The graph was constructed by the following formula:

$$\begin{cases} Err_i = \sqrt{(x_f - x_v)^2 - \left(y_f - y_v\right)^2} \\ Err_i \leq \varepsilon_i \end{cases} \quad (14)$$

The fuzzy logic algorithm is used to estimate the actual tooth area of the gears. The performance results given by our approach were compared to the performance of these data using the ideal model.

It is clear that the use of the fuzzy logic estimator is appropriate and estimates the actual area of the tooth which consists of a very complicated path when detecting teeth by CMMs in the sense that the application of the logic technique with estimation of dynamic non-linear systems, special cases, and the surface of the gear which contains several parameters is the best (see **Figure 13**).

Anyway, this problem is solved by this approach. Thus, the role of this work is the determination of the tooth curve to estimate the shape defect of the gears. In our future work, we will try to implement other learning algorithms such as the Kalman estimator or fuzzy neuron.

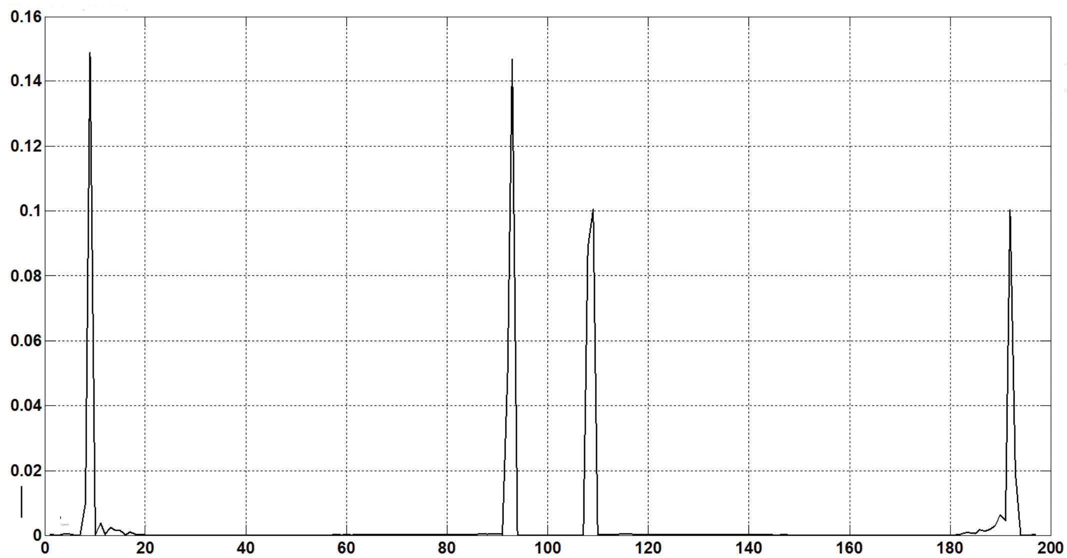

Figure 13. Calculation of the error of the result of the fuzzy logic and the normal vector.

12. Conclusion and perspectives

In this respect, we can conclude that by the principle of fuzzy logic, there is not really the right or the wrong answer as has already been pointed out several times. While the choice of calculation method the profile taken is conditioned between the installation and the performance according to the designer.

Some researchers even suggest averaging the different methods, but this is not a generalization, and the calculations become even more complicated. Finally, we mention that this problem of probing is solved, thanks to the development of the fuzzy logic, which relies on the linguistic knowledge, nonlinearity, and not the needs of the model; the solution was obtained by means of a computer. Nevertheless, it lacks precise guidelines for the design, because of contradictory inference rules.

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