Evaluating the Detected Errors in Fluid Transmission Pipelines by Smart Magnetic PIG in The Presence of External Magnetic Fields

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Abstract
In this paper, evaluation of errors detected in the fluid transmission lines by magnetic PIG in the presence of external magnetic fields, using Fuzzy Inference System, FIS, in order for classification of deterioration and the diagnosis of the deterioration type of structural defects of steel pipes in the petrochemical industry has been done. The set of features mentioned in this article are: 1) geometric features extracted from the raw data of the smart magnetic PIG, 2) features resulting from the response of the model to the current situation. Initially, the strategy of testing is defined and then the required data are collected using MATLAB software. Then, with the help, a parametric transfer function for each pulse is obtained. When the data are considered as the input of the function, it will also be used as the output. 3 selected modes of pipes in this paper are: healthy state, worn and defected. Therefore, the defected state refers to synthetic metals or any other defects. Then, the required characteristics are calculated and they are used in the Fuzzy Inference System as input in the classification section. The obtained system has high capability for classification and detection of deterioration of the pipes with minimum error alarm and low dissatisfaction.

Key words
Detected error, fluid transmission pipeline, PIG, magnetic fields

1. Introduction:

Today, natural oil and gas and chemical raw materials are among key energies that play a central role in people's lives, industrial manufacturing, agriculture and national defense. Properly, it is known that the safest way to transfer oil and gas is using pipeline. However, many of the fluid transfer lines are buried underground where they are easily affected by humidity and pressure and are prone to deformation and corrosion. Any small metal corrosion or defects in pipelines can cause serious and costly accidents [1]. Another problem is passing of the pipeline from under or near high-voltage transmission lines that due to magnetic performance of the smart magnetic, the magnetic fields resulting from power transmission lines has great effects on this system [2].

The pipelines Industry in Iran has developed along with the oil industry and the gap between Iran and the developed countries of the world should be reduced gradually; especially in the fields of engineering and technology of designing pipelines, the construction level, operation management and maintenance. But Iranian pipeline industry has slowly developed and there is a very significant split in the coverage of pipelines, range of services, technical equipment and so on. Oil and Gas Company has plenty of facilities and equipment that ensuring of optimal and safe performance in this context is important. The cost of repairs or replacement of subsea pipelines is much more than pipes on the land and protection of pipelines requires great cost. Safety of vertical pipes (storage pipe) of deep waters is necessary and in order for operation on offshore platforms, there is need for evaluating the damages and estimating the pipes deterioration. There are some defects in the spiral welds in some old and long pipelines of Iran. This defect has been formed due to lack of proper fusion during pipe production and annually the costs of repairing and maintenance of pipelines in Iran is about several hundreds of million dollars and this process is increasing. Limited technology of the tools and diagnostics results in a waste of manpower, material and financial resources. All of these lead to the point that the subject of use of modern technologies such as smart magnetic systems in accurate and timely detection of possible errors in the pipelines is of great importance [3].

2. Deterioration:

Deterioration of metals in humid environments occurs due to electrochemical properties. When two or more electrochemical reactions occur, deterioration will be the result. As the result of these reactions, some properties of the metals or alloys will change from metal to non-metal form. In the attachments [4] and [5] the most common types of deterioration can be seen. Classification of deterioration type is done based on morphology of the

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attacks. In this paper, concentrated deterioration is selected as the main type of deterioration and will cause problems in the metals. Also three states of metals as: worn, defected and healthy will be examined with the help of recommended methods.

3. Experimental design:

In this paper, data and information related to smart magnetic PIG sensors which can be seen in Figure 1 and the magnetic field of 400 KV (Figure 2), the noise created by the field (Figure 3) have been simulated by MATLAB software and are showed in the form of a single-dimension scheme, and then using adaptive filtering, the noise created by the field is taken.

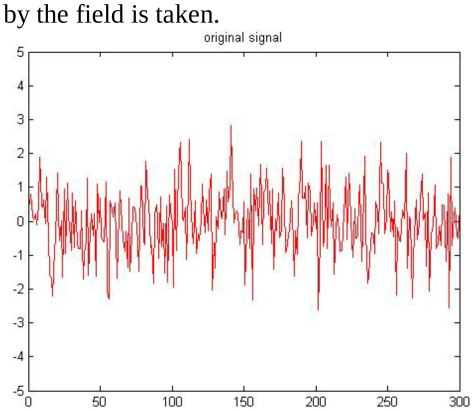


Figure 1: Signal of smart magnetic PIG, simulated by MATLAB software

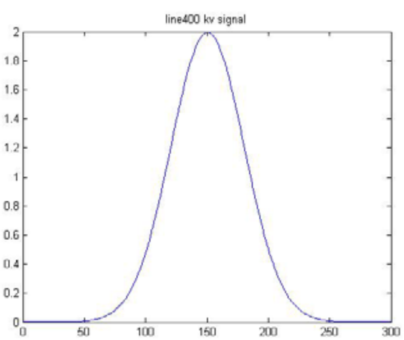


Figure 2: Signal of 400KV field, simulated by MATLAB software

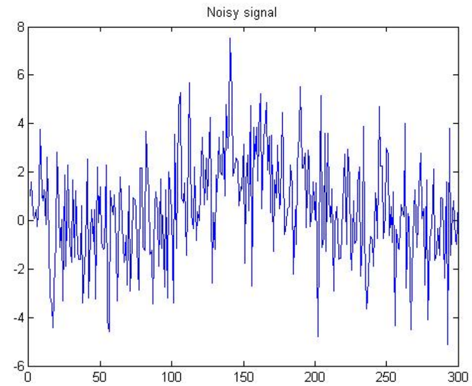


Figure 3: Noise signal, simulated by MATLAB software

Signal filter

In the following figure the diagram block of an adaptive filter is shown. As is seen in Figure 4, in order to identify the unknown system, the input is applied into the system and the filter in order to bring the measurement error to zero.

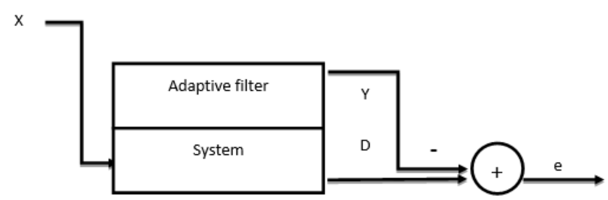


Figure 4: Diagram block of comparative filter

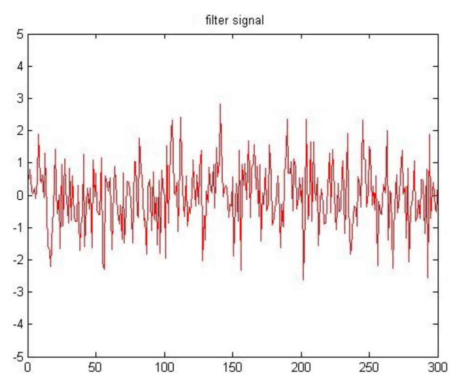


Figure 5: signal filtered by comparative filter

4. Deconvolution:

In order to have a better picture of the states of metal, echo of the pulse obtained from the state function is separated from the signal of response of the measuring system. On this basis, the properties of the above signal are analyzed. A particular group of geometrical models as linear systems invalid with time or LTI in accordance with the impulse response are modeled [6].

Now let's consider h(t) as the impulse response in the specific group of u(t) for the healthy metal; y(t) also measures the ultrasonic pulse echo and then the output of LTI system can be stated as the following formula and in accordance with Figure 2:

$$y(t) = h(t) \otimes u(t) + \eta(t), \qquad (1)$$

In this formula, $\eta(t)$ is the increased output noise (non-Gaussian or Gaussian noise) and $\otimes$ is the time complexity. With the help of the obtained values of $h(t)$ in Equation 1, the echo pulse amount and the response of measuring system can be achieved by detecting, filtering and deconvolution of system.

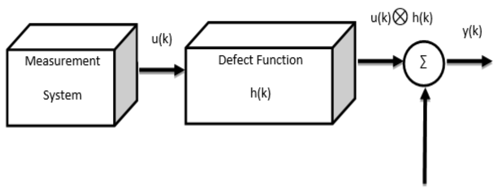


Figure 6: defected ultrasonic model

Since the main objective of deconvolution is to achieve an appropriate model for the impact function, so the above model can be created with the help of numerous methods. In this regard, the Auto Regressive Moving Average (ARMA) model is considered a suitable linear approximation model for any kind of real system. Using the coefficients model enables to improve system performance.

The resulted system is in the form of an ARMA process which is shown as the transfer function in the following form:

$$H(z^{-1}) = \frac{Y(z^{-1})}{U(z^{-1})} = \frac{b_0 + b_1 z^{-1} + \cdots + b_{n_b} z^{-n_b}}{1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_{n_a} z^{-n_a}}, \qquad (2)$$

In this equation, n_a and n_b are the degrees of polynomials in the numerator and the denominator. H.Y.U are also measured input, output and the impulse response frequency of the smart magnetic PIG sensors, respectively. The coefficients a_s and b_s in this system are related to the input and output signals.

5. features space:

In order to become completely familiar with wave transformation, firstly a set of measured values called "Features" should be known. There are several methods in order to select a desired set of features. As was stated in abstract and introduction, using NDE depends on the persons' specialty. NDE technicians, with the help of their experiences, classify the defects of the model. In order to improve this process, countable parameters can be used. The selected features in this article are:

1. Experiences of NDE specialists and
2. Impulse response of the system

6. Human explorations:

In order to get familiar with the mechanism of classification of metal health, professionals and specialists can help us through filling questionnaires. In fact, using the results obtained from these questionnaires, the different kinds of defects existing in the gas transfer pipelines can be identified better (Figure 7). According to Figure 7, it can be concluded that the x-axis in all samples shows the distance in millimeters between each wave and the y-axis shows the normalized intensity of waves. Although in this figure there is nothing about the amount of wavelengths, however, this information can be used in order to examine the shape and spatial situation of the deficits.

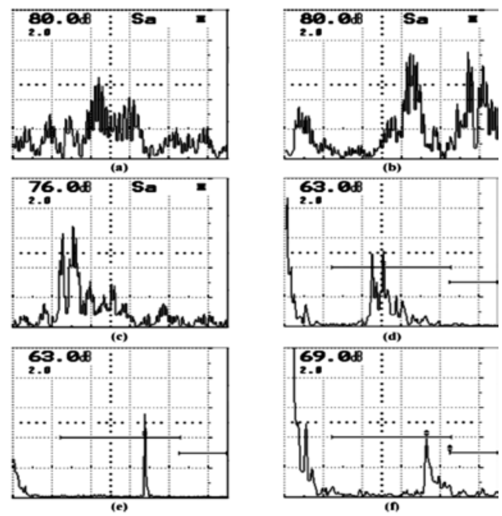


Figure 7: the different kinds of data related to the a) holes, b) light deterioration, c) gaps, d) joints, e) cracks, and f) resulted from partial melting

According to Figure 7, the following points are obtained:

1. Cracks usually cause very sharp peaks and have no effect on the peak of adjacent elements.
2. In relation to the numerous cracks that have formed close to each other, any similar peak is formed near the other one and they evolve together.
3. The gaps also cause formation of special cracks that its reason is the interaction of the cracks with each other with the same energy and the diffusion of each crack in its surroundings.

4. Partial melting (LoF) can cause creation of different slopes in the materials and due to the difference in speed of ultrasonic waves, welding will not be done well.
5. Usually the cracks and joints have similar wave form and their separation and identification is difficult. This point also applies to the cracks and LoF.
6. One of the reasons for the lack of echo in dB same scale in various situations is lack of proper ultrasonic wave energy in the materials.
7. If dB enters a new position, therefore echoes will be formed in that situation. This means that in the small dBs, the waveform of the deterioration is too weak and is similar to the noise pattern. However, when the dB scale is changed, the above waveform will also be changed.
8. The amounts of noise signals which are called grass can show the existence of deterioration and corrosion in the metal. Such case occurs in dB 20 scale. If grass arises, therefore, the noise intensity cannot affect grass pattern.
9. Change of the position of echo to the new position indicates some anomalies in the base metal and the term base metal is used when the casting steel is poured into the molds between each two base metals. In this regard, when ultrasonic inspection is performed, the reflection resulted from welding will show the base metal.
10. Changes in the shape and position of the echo are affected by sharp and cutting edges of the metal.
11. Any deviation and curve can impact the echo transfer time and thus the resulted peak will have a more different shape compared to the normal peak.

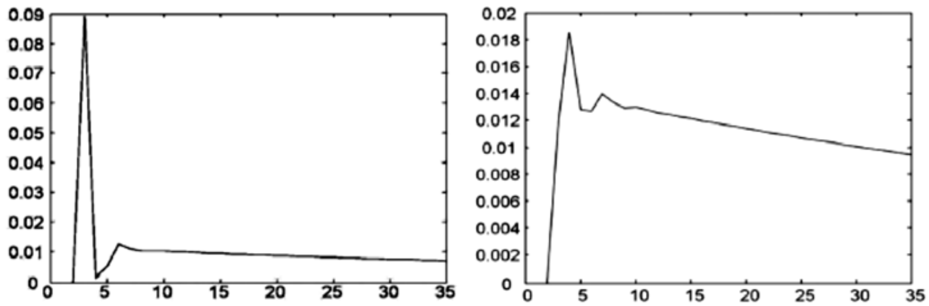
7. Impulse response characteristics:

When we consider the study sample, we find that the use of computational methods can be problematic. In the data, many overlays and common points between characteristics have been observed. In this situation, deconvolution can be very useful.

Using this reference input along with signals measured from the different samples having corrosion, defects and normal samples have been examined. Healthy metal, compared to other elements has gained greater attention. Of course, large differences in the worn and corroded samples have been seen with other elements. Now, we compare the elements of this group with the other two groups and find out their conditions. It can be said that the small obtained particles have good tolerance in order to be used in various industries.

When the transfer function for each pair of input-output data is obtained, some features can be extracted from the waveform of the impulse response in this function and can be used in order for classification of the raw data. With the help of a third order transfer function, the reference signals can be obtained and be used to predict the next output of the function. It means that the amount of nb will be equal to 1 and na will be equal to 3. In Figure 8 you can see a number of images related to the impulse response. In all these images, the x-axis represents the sample index (k) and y-axis represents the normalized values.

Figure 7 shows some responses of the reaction. The following observations have been obtained from these responses in all samples:
1. Healthy metals usually have multiple peaks and negative peaks.
2. Cracks have waveform with a light slope.
3. The gaps also have relatively weak peak.
4. Deterioration has light peak but however, its peak is dense.

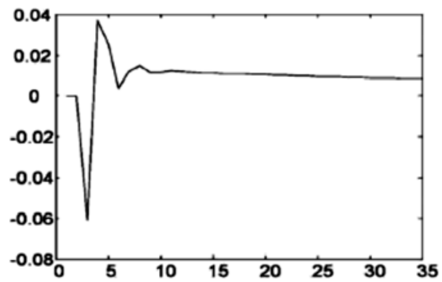


$$H(z)_{corroded} = \frac{0.0895 - 0.0744z^{-1}}{1 - 0.8467z^{-1} - 0.0446z^{-2} - 0.0896z^{-3}}$$

(a)

$$H(z)_{defective} = \frac{0.0119 - 0.0108z^{-1}}{1 - 0.6476z^{-1} - 0.0629z^{-2} - 0.2694z^{-3}}$$

(b)



$$H(z)_{healthy} = \frac{-0.0610 - 0.0806z^{-1}}{1 - 0.7147z^{-1} - 0.0163z^{-2} - 0.2466z^{-3}}$$

(c)

Figure 8: impulse response and the obtained transfer functions of a) corroded metal, b) defected metal and c) healthy metal.

8. Mapping and indexing of features:

In order for efficient use of the findings of specialists and also the features based on impulse response, in this paper, some of mapping methods which are called “main features” will be used. These kinds of features are mentioned below. As an example, the index of amplitude ratio (volatility) to the width (AWR) can be used in order for determining wavelength of thick and thin peak and also scattered waves; the amplitude of adjacent peaks affects the amount of wavelength and in order to determine the gentle slope and the steep slope of the impulse response also the slope coefficient can be used. dB values can be used in order to determine the deteriorated grass to noise signals. Space under the grass shows the intensity and power of deterioration and corrosion. The above features include:

1. The number of peaks in the impulse response of NP,
2. The amplitude and intensity of the first peak,
3. The ratio between the first peak and the second peak,
4. The ratio of amplitude to the width of the main wavelet of AR,
5. The ratio of the slope of two halves of the sequence of impulse response of SR,
6. Measuring the settings of dB and the device of dB,
7. The space under grass (in this space, the grass intensity is less than 25 percent of the peak wavelet),
8. Values related to the elements with different corrosions or incomplete waveform of the identical samples which is showed by CXY.

9. Fuzzy Inference System:

Investigating the human perception in accordance with general understanding of NDE experts from the available information, it is possible to make favorable decisions in order to maintain, select, and replace the metals. Fuzzy logic method is considered one of our favorite methods. Although this tool converts the discovered information into quantitative data, it also is able to, using objective laws, use decision making of people. Thus, according to the volume of information available, the efficiency of the proposed system must be examined. In fact, once the NDE personnel constraints be considered in this context, then these constraints will be the main objective of the system. Meaning that accuracy of NDE process will be constrained due to fatigue, decreased mental and physical care and misunderstanding of the issue by the experts.

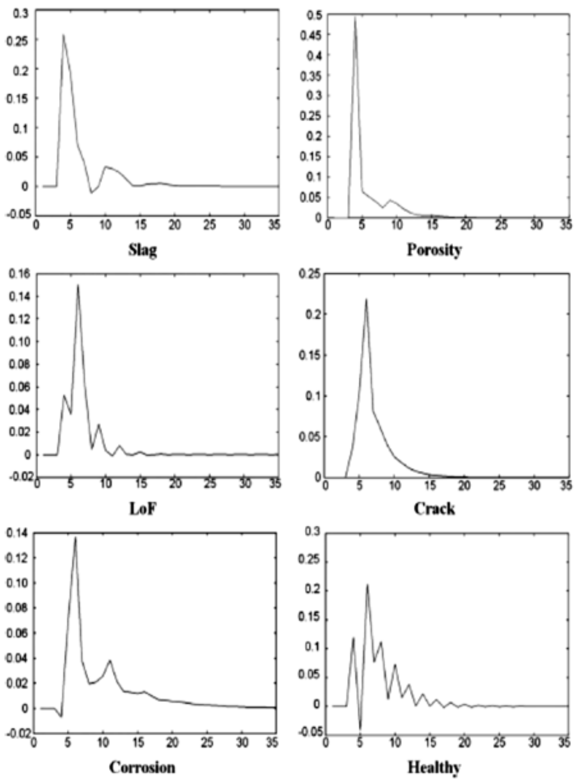


Figure 9: impulse response for different metals

In Figure 10, the recommended FIS which is composed of the following points is showed:

. 8 descriptors of input membership functions (showing the feature's space)

. 3 descriptors of output membership functions and

. A set of principles related to the different degrees of outputs membership functions.

10. Input and output membership

In each input of features, a set of elements called input membership functions have been defined. These functions have various degrees according to below points:

1. All the values related to the input feature are classified in the outputs group (see Table 1).
2. According to the Table's values, the range of numbers have been determined in 3 groups of outputs.
3. In this paper, each of membership functions has been classified in 3 membership degrees. Each degree also has a special name appropriate for the kind of membership. For example, the group of "the number of peaks NP" has a value with 3 degrees of membership.
4. Each of these degrees now is showed with the help of a mathematical function and the input amount of each feature along with its weight has been selected as the input data of the model.
5. In MATLAB software, there are 11 different membership functions. Obtaining the best result depends on your selected kind of strategy and on this basis, there are 5 known membership functions: triangular function, gbellmf, Z function, trapezoidal, and S function. At each time, different combinations of these membership degrees can be selected and be evaluated with the help of similar principles.
6. The obtained membership functions are a combination of different membership functions (Figure 9).
7. Output variables corresponding to three degrees of membership represent 3 different modes of metal. Each of these membership functions are related to triangular distribution and appropriate to different degrees. Their numeric distribution is as follows:

a) Very low: complete trimf between 40% - 40% with a center at 0%

b) Low: complete trimf between 10% - 90% with a center at 50%

c) Too much: complete trimf between 60% -140% with a center at 100%

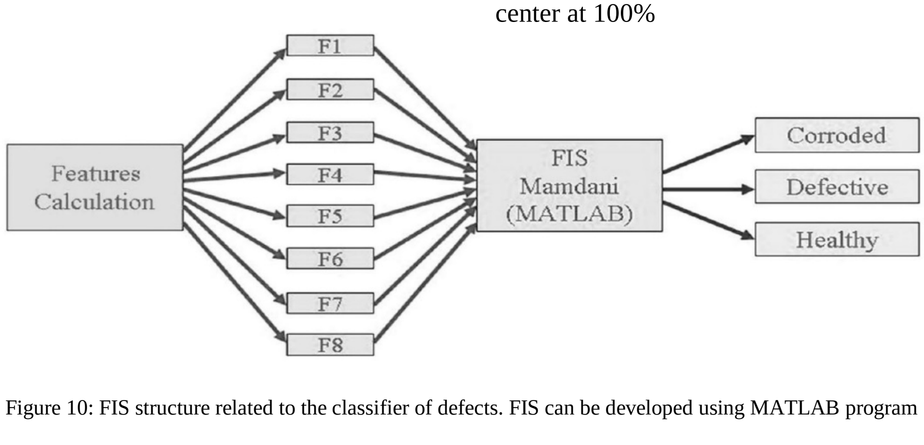


Figure 10: FIS structure related to the classifier of defects. FIS can be developed using MATLAB program

Naming and degree of membership functions has been mainly ad hoc that this point depends on familiarity of the user with the system. Figure 11 shows the input values of each input membership function; x axis between 0-1 represents the overall probable space.

11. The rules base:

Rules are a set of components and the rules' results that are generally accepted by people. In this case, a set of 11 rules can be created based on research studies. These rules include:

1. If (NP is small amount) and (the first amp is high) and (ratio of peak is average) and (AR is normal) and (slope coefficient is high), so (metal is much likely to be in a healthy condition) (risk of corrosion is very low) (risk of having defects is also very low).
2. If (NP is high) and (the first amp is normal amount) and (ratio of peak is average) and (AR is deteriorated) and (slope coefficient is high), so (metal is less likely to be in a healthy condition) (risk of corrosion is very high) (risk of having defects is also very low).
3. If (NP is high) and (the first amp is low) and (AR is abnormal) and (slope coefficient is average), so (metal is less likely to be in a healthy condition) (risk of corrosion is very low) (risk of having defects is also very high).
4. If (AR is deteriorated), so (metal is less likely to be in a healthy condition) (risk of corrosion is very high) (risk of having defects is also very low).
5. If (NP is high) and (the first amp is low) and (ratio of peak is average) and (AR is deteriorated) so (metal is less likely to be in a healthy condition) (risk of corrosion is very high) (risk of having defects is also very low).
6. If (NP is low) and (the first amp is low) and (ratio of peak is also low) and (AR is normal) and (slope coefficient is high) so (metal is much likely to be in a healthy condition) (risk of corrosion is very low) (risk of having defects is also very low).
7. If (NP is normal) and (dB is normal), (Cxy is normal) and (grass is normal) so (metal is much likely to be in a healthy condition) (risk of corrosion is very low) (risk of having defects is also very low).
8. If (AR is defected) and (dB is defected), (Cxy is defected) and (grass is defected) so (metal is less likely to be in a healthy condition) (risk of corrosion is very low) (risk of having defects is very high).
9. If (AR is corroded) and (dB is corroded), (Cxy is corroded) and (grass is corroded) so (metal is less likely to be in a healthy condition) (risk of corrosion is very high) (risk of having defects is very low).
10. If (dB is defected) so (metal is less likely to be in a healthy condition) (risk of corrosion is very low) (risk of having defects is very high).
11. If (dB is normal) so (metal is much likely to be in a healthy condition) (risk of corrosion is very low) (risk of having defects is also very low).

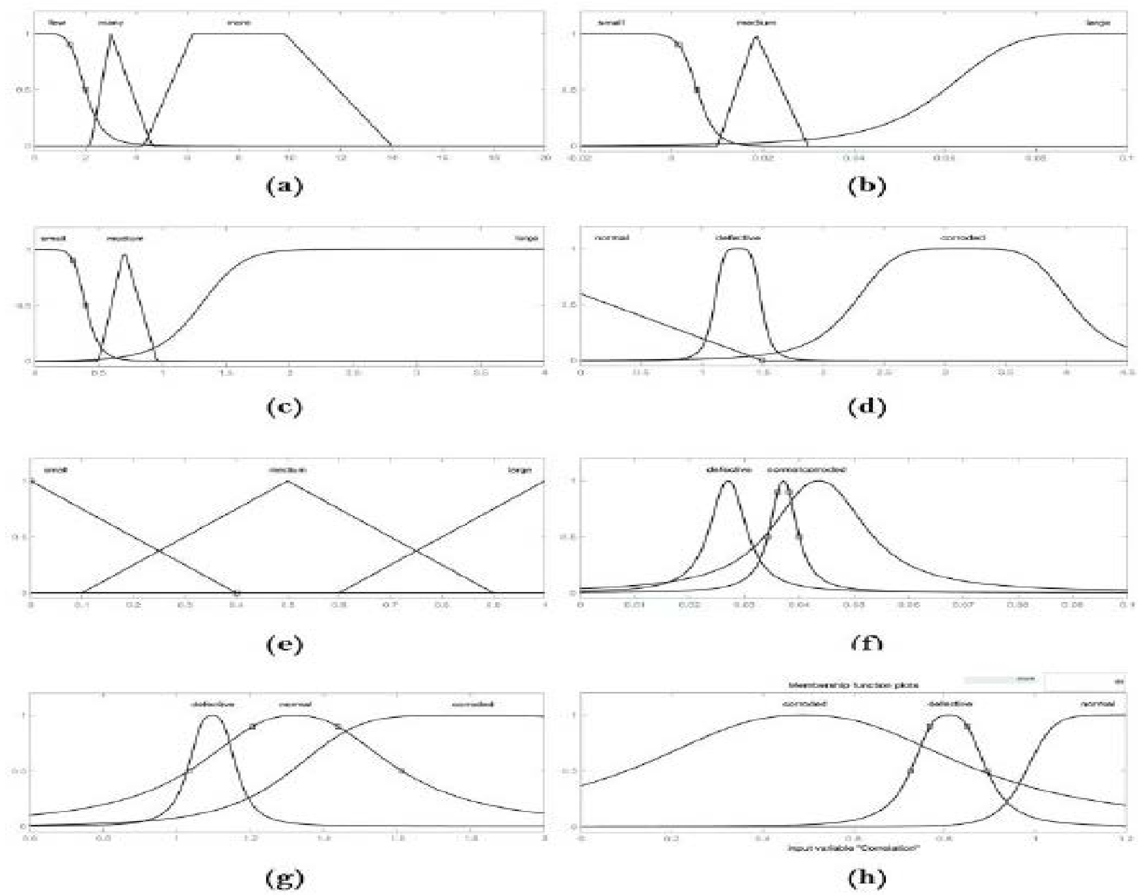


Figure 11: different components of FIS.

Membership input functions for (a) F1 = NP, (b) F2 = 1st Amp, (c) F3 = Peak ratio, (d) F4 = Slope ratio, and (e) F5 = dB, (f) F6 = AR, (g) F7 = Grass, (h) F8 = Cxy, and membership output functions which are healthy, defected and corroded. X axis is the membership input variable and y axis is probability space between 0-1.

Table 1: selecting membership degrees for the feature's space

	F1 = Number of Peaks (NP)			F2 = 1st Amplitude (1st Amp)			F3 = Peak Ratio (PR)			F4 = Slope Ratio (SR)		
	F	Mn	Mr	S	S	S	S	Md	L	S	Md	L
H	10		15	−0.6	−0.6	−0.6	0.12	2.13		−0.6		1.5
C	9	12	14	0.4	0.4	0.4	0.07	1.8		0.4		2.2
D			18						3.8		1.14	
	F5 = Decibel Settings (dB)			F6 = Amp Ratio			F7 = Grass			F8 = Correlation		
	N	D	C	N	D	C	N	D	C	N	D	C
H	56–68			0.03–0.047			0.9–1.6			1		
C		64			0.02–0.03			0.5–0.76			0.5–0.76	
D			72–80			0.02–0.06			1–1.6			0.1–0.94

F = Few, Mn = Many, Mr = More; S = Small, Md = Medium, L = Large; H = Healthy, C = Corroded, D = Defective, N = Normal. Empty cells represent no data item in that range.

Making the above rules depends on the feature of the model. In this regard, there are three views:

1. None of the rules can be used in algebraic or statistical decision makings. In fact, they are just very simple phrases and are used to communicate between membership values and various outputs.

2. Rules base components have a direct relationship with the defined degrees of membership. For example, Table 1 shows that in a healthy metal, the number of peaks is very few (1 to 2 cases), the peak amplitude is wide and peak width is also low and the downward slope compared to upward slope in impulse response is sharper. Therefore, designing and building rules' base for this classifier must be done carefully.

3. In fact, it is not possible to mention all the features in this article. Therefore, we put all our focus on increasing confidence level in the existing classifier. For example, Rule ≠ 11 is related with an independent feature in a group for example group of healthy metals. This feature alone is able to detect healthy metal and is compared with other properties similar to itself.

When restrictions occur in the model, the general decision-making method can be used. In each set, the input values, geometrical coordinates of decision-making area are calculated and its overlaps and common points with other rules in the input membership function will be measured. This geometrical coordinates can be used as an indicator of the degree and using its help, input and output degree of cracks, gaps or defects related to partial melting can be determined. As a result, the decision made is multi-dimensional and it cannot be considered as a distinct factor. In Figure 12, you can see some subsets of decision-making levels.

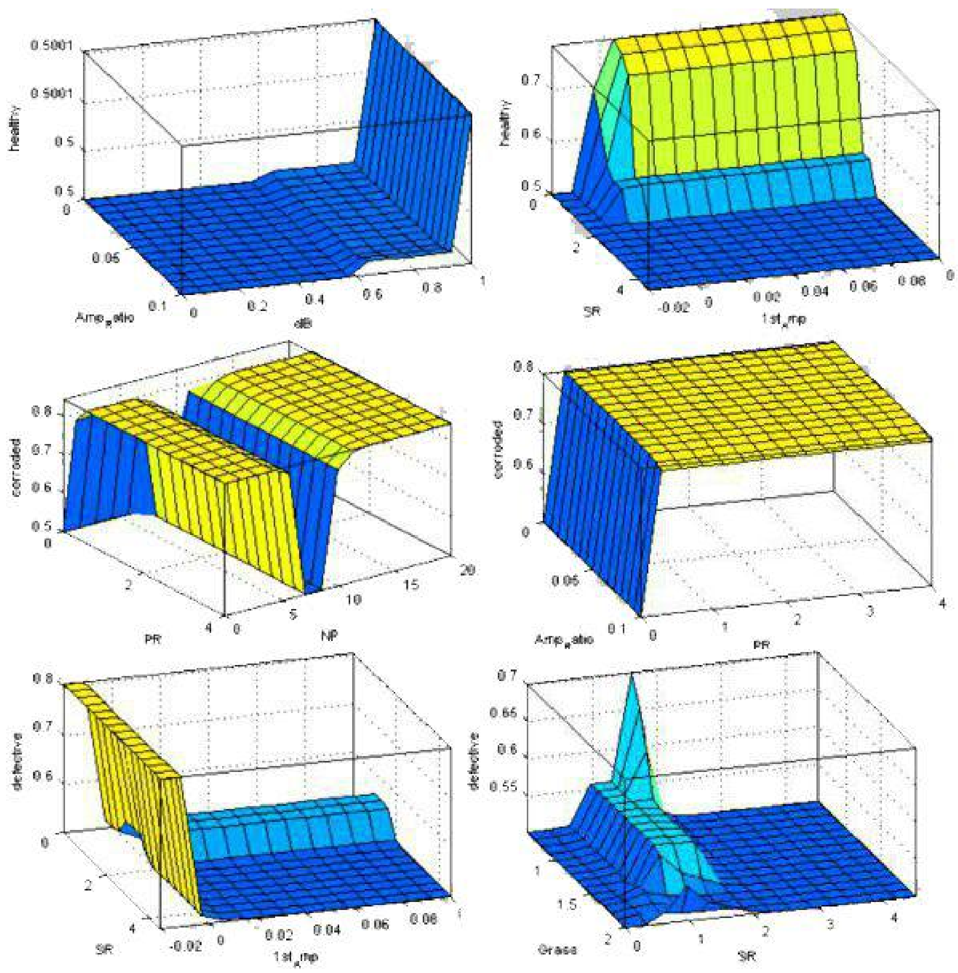


Figure 12: decision making levels

for a) healthy condition for AR, dB; b)healthy condition for FP, SR and c) corroded condition for PR,NP; d) corroded condition for PR, AR; e) defected condition for FP, SR and f) defected condition for dB, Grass.

Table 2: Comparing the results related to training data

healthy	corroded	defective	TRUE	FIS	
0.82	0.5	0.5	1	1	
0.81	0.5	0.5	1	1	
0.81	0.5	0.5	1	1	
0.81	0.5	0.5	1	1	
0.81	0.5	0.5	1	1	
0.81	0.5	0.5	1	1	
0.81	0.5	0.5	1	1	
0.81	0.5	0.5	1	1	
0.81	0.5	0.5	1	1	
0.81	0.5	0.5	1	1	
0.81	0.5	0.5	1	1	
0.81	0.5	0.5	1	1	
0.5	0.82	0.5	2	2	
0.5	0.82	0.5	2	2	
0.5	0.83	0.5	2	2	
0.5	0.83	0.5	2	2	
0.5	0.83	0.5	2	2	
0.5	0.81	0.5	2	2	
0.5	0.81	0.5	2	2	
0.5	0.81	0.5	2	2	
0.82	0.81	0.5	2	1	
0.81	0.81	0.5	2	2	X
0.5	0.5	0.5	2	1	
0.5	0.5	0.83	3	3	X
0.5	0.5	0.81	3	3	
0.5	0.5	0.85	3	3	

12. Results and findings:

The proposed system was evaluated in 27 samples with 3 healthy, defected and corroded states. These input features were examined in all wave charts and in order to calculate output, were entered the FIS. Decision making in order to use FIS depends on selecting amplitude from among 3 groups of healthy, corroded and defected metals. Using defuzzification method, we can calculate the values of each of output membership functions. In Table 2, you can see the result of this test. Although no concept of the way of training FIS in a neural network is mentioned, but its primary structure can be used as values of the set of data (or training data). However, only specific coordinates of the data can be used in classification.

In order to verify the performance of the algorithm and the accuracy of FIS, a new set of 10 samples (3 cases of healthy metal, 4 cases of defected metal and 3 cases of corroded metal) must be acquired. The use of these samples is just like the training stage, however, attention must be paid to thickness and type of metal too. In Table 3, the results of this test data have been mentioned.

Table 3: Comparison of results of test data

healthy	corroded	defective	TRUE	FIS	
0.5	0.802	0.501	2	2	
0.5	0.5	0.805	2	2	
0.8353	0.5	0.5	1	1	
0.8215	0.5	0.8312	3	3	x
0.8117	0.5	0.837	3	3	
0.5	0.8388	0.5	2	2	
0.8117	0.5	0.8459	1	3	
0.8117	0.5	0.8272	3	3	
0.5	0.8071	0.5	2	2	
0.8478	0.5	0.5	1	1	

The results of FIS general classification along with the obtained data sets are expressed as follows:

. Correct classification of corrosion rate of 87 percent
. Correct classification of defects of 100 percent
. Identification of healthy metal of 94%
. Incorrect classification of corrosion or defects of 3%
. Error alarm due to corrosion or defects in metal of 5.4%

According to the studies in the field of industry, much effort have been done in order to use rules and degrees of membership in the input features. Totally, the false classification had been more than 10 percent and error alarm had been 20 percent which in the industry, these values are accepted.

The reason for creation of the incorrect classification and error alarms include:

1. Rules base requires uniform mixing of membership values with each other.
2. There is no separate rule focusing on just one group.
3. Inconsistent sampling of data has occurred due to human error.

In general, the proposed technique investigates the algorithmic structure and its efficiency in decision making and classifying of defects. With the help of the mentioned methods, the physical features of the form can be converted to countable features and the fuzzy rules can be converted to personal views. In this method, inference heuristics has turned to cumulative knowledge, although it faces limitations from the staff side. This article can improve adopting decisions by NDE personnel and help them in diagnosis of right from wrong.

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