Thickness Measuring of Thin Metal by Non Destructive with Fuzzy Logic Control System

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Abstract
Non-Destructive Testing & Evaluation methods are developed to inspect and investigate materials and structures. Ultrasonic Testing is an NDT method can be used for measuring the thickness of objects, as one of its significant applications. The objective of this paper is designing and applying an intelligent UT fuzzy control system for evaluating the thickness of thin metal objects in a range of 5-20 mm. The designed Fuzzy Logic Controller has five variables including four inputs and one output. The inputs are frequency of probe, couplant's acoustic impedance, object's acoustic impedance, and temperature; also the output is thickness, particularly of thin objects. This suggested method has been applied to four metals. Our strategy consists of three steps; and it has been preferred to utilize pulse-echo method because of using the immersion method. The experimental results imply that the proposed procedure has been able to control and measure the thickness of thin objects (5-20 mm) successfully within a rate of mean error of 0.5%.

Keyword
Non-Destructive, Fuzzy Logic, Thin, Control

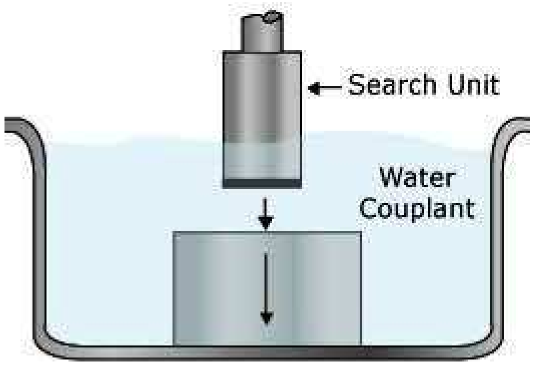
1. Introduction

Coating measurements with high precision and high resolution is an important issue in process and quality-control. Traditional nondestructive measurement methods like eddy current were limited to the substrate material and could not measure individual layers. Sound energy above the audible frequency of 16 kHz is designated as ultrasonic [1]. Sound waves are able to travel best through rigid solids rather than through liquids and gases. These waves have a quantifiable speed, wavelength and frequency. Owing to these properties, sound waves have scores of uses. Ultrasonic Testing (UT) [2] is considered as one of the modern technology that would allow engineering constructions and solid materials to be checked and it detects internal faults while keeping structures intact and undamaged. UT uses acoustic waves to disseminate through the material to test and detect any irregularity. UT can be used on a wide variety of plastics, composites, ceramics and metals but cannot be used on wood and paper products. UT device would consist of a receiver, transducer and a monitor where the transducer would generate high frequency sound waves which would propagate through the material being tested [3, 4].
It is known that thickness measurement is one of UT's applications. This measurement is widely applied as the testing method for examining the degree of wastage and corrosion of the pipes or equipment. The UT's data are obtained using the pulse-echo method in the perpendicular method [1, 5]. Generally, ultrasonic probe is applied by transmission pulse when direct contact method is considered. In this paper, it is utilized a pulse-echo method with appropriate immersion circumstances between an ultrasonic probe and an aimed object. An evaluation system by pulse-

echo method using a fuzzy logic inference is described. Fuzzy Logic is also used broadly in Artificial Intelligence (AI).

FLCs are rapidly becoming a very suitable viable alternative for old controllers [6,7]. The fuzzy controller is able to behave in a similar way to the human control processes [8]. As an advantage, it is not required mathematical modeling in fuzzy logic. Particularly, the rules of FLC are based on the familiarity of the system's manner and the experience of the respective expert or engineer.[9] Fuzzy logic control is an algorithm for non-mathematical decision which its basis is on respective operator's experience [10, 11].

It has been developed a method for evaluating the thickness of objects of 5 to 20 mm by integrating UT and FLC. As the result of our experiments, the proposed procedure was able to increase the accuracy of thickness evaluation for thin objects up to an acceptable and desired level.



Figuer1. A normal single-beam probe (transducer) in an immersion method [10]

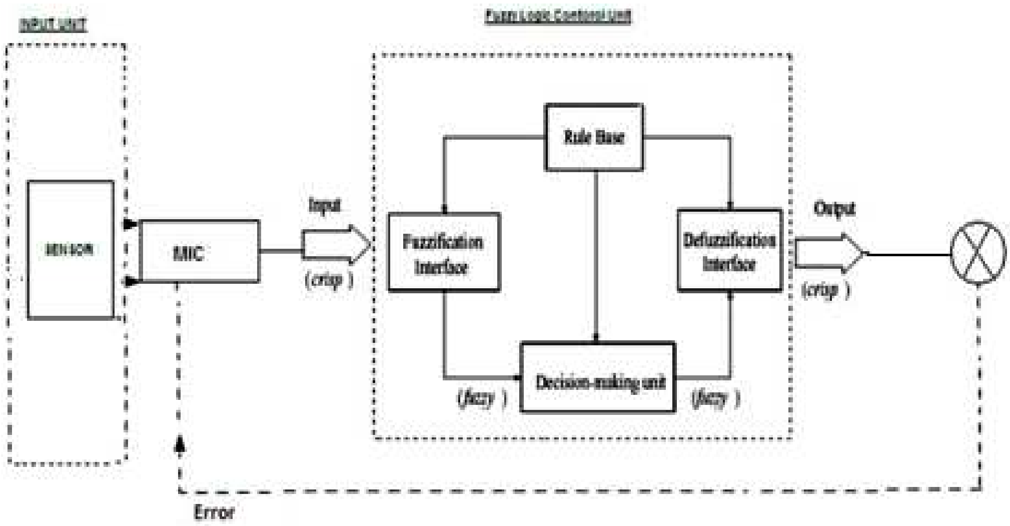


Figure2. General architecture of a FLC

2. Methods

In this study, we employ three so-called Couplant Materials for immersing the probe and objects, including Water, Petroleum and Glycerin. Our strategy consists of three steps. At first, we locate the surface of the object by detecting a surface echo-beam from an obtained waveform. In the second step, we locate the bottom (next surface) of the object by using a fuzzy inference. At last, we determine the thickness from the surface point and the bottom point of the object.

The type of probe in our experiment is a Normal Probe (Normal Single-Beam Transducer), Fig.1. It is both sender and receiver. The Piezoelectric Material (PM) applied in this probe is $Pb\ Nb_2\ O_6$. That why we selected this kind of PM is just for its four remarkable properties: 1.Appropriate piezoelectric property; 2.High resolution power and sensitivity; 3.High temperature endurance (< 550°C); 4.Producible in a rather large number. In addition, objects' section must not be circular and they are in cubic form. This assumption is set just for ease of doing experiments and more accessible accurate outputs. In this approach; inputs are categorized into four main groups: probe frequency, specimen's acoustic impedance, couplant acoustic impedance and circumstances' *temperature* that would be discussed in following.

2.1 Probe Frequency

Usually, the frequency in UT (of PM applied in probes) varies from 0.5 to 20MHz; while the most common limit is between 0.5 and 6MHz; therefore it only fuzzificate the range of 0.5-6MHz. Specimen's Acoustic Impedance**.** For the metals examined here, it is in 150 - 500 [$*10^4$ g/cm^2.s]. The specimens consist of Aluminum (Al), Iron/Non-Alloy Steel (Fe/NA-St), Gray Cast Iron (GCI) and Copper (Cu), Table 1.Couplant's Acoustic Impedance. The couplant material was chosen depending on target specimen features. The acoustic impedance of mentioned couplants is declared in Table 1.Circumstances' Temperature. This parameter has almost direct effect on the density of the fluid applied as couplant. Almost always, couplant's density decrease when temperature increase. Thus we decided to limit it from 20 to 30°C. The designed FLC has four inputs and one output as mentioned above. The output is the recognition signal (u). Both fuzzification and the inference system were tuned experimentally. The algorithm used for inference is the Max-Min method, and the Center of Area (COA) method was used for the defuzzification in order to get the best results. In Fig. 2, the general architecture of an FLC is shown. It consists basically of four stages. The first stage is to obtain a set of rules for the fuzzy controller. It will be executed by using the *Fuzzy Tech toolbox* and it will be tested by using an in-*vitro model*. The next step is to test the set of rules directly in vitro process control condition. These inputs will be evaluated using a fuzzy logic-based control algorithm and an output signal will be produced. The digital output signal will then be fed into a converter via micro controller and connected record the thickness results. In this closed loop control system, the output is labeled as Low (L), Very Low (VL), Medium (M), etc. The inputs and output measured quantities are real numbers (crisp). The process of converting a numerical variable into a fuzzy variable is called fuzzification. Fig.3 shows the membership functions that are used to fuzzify the inputs.

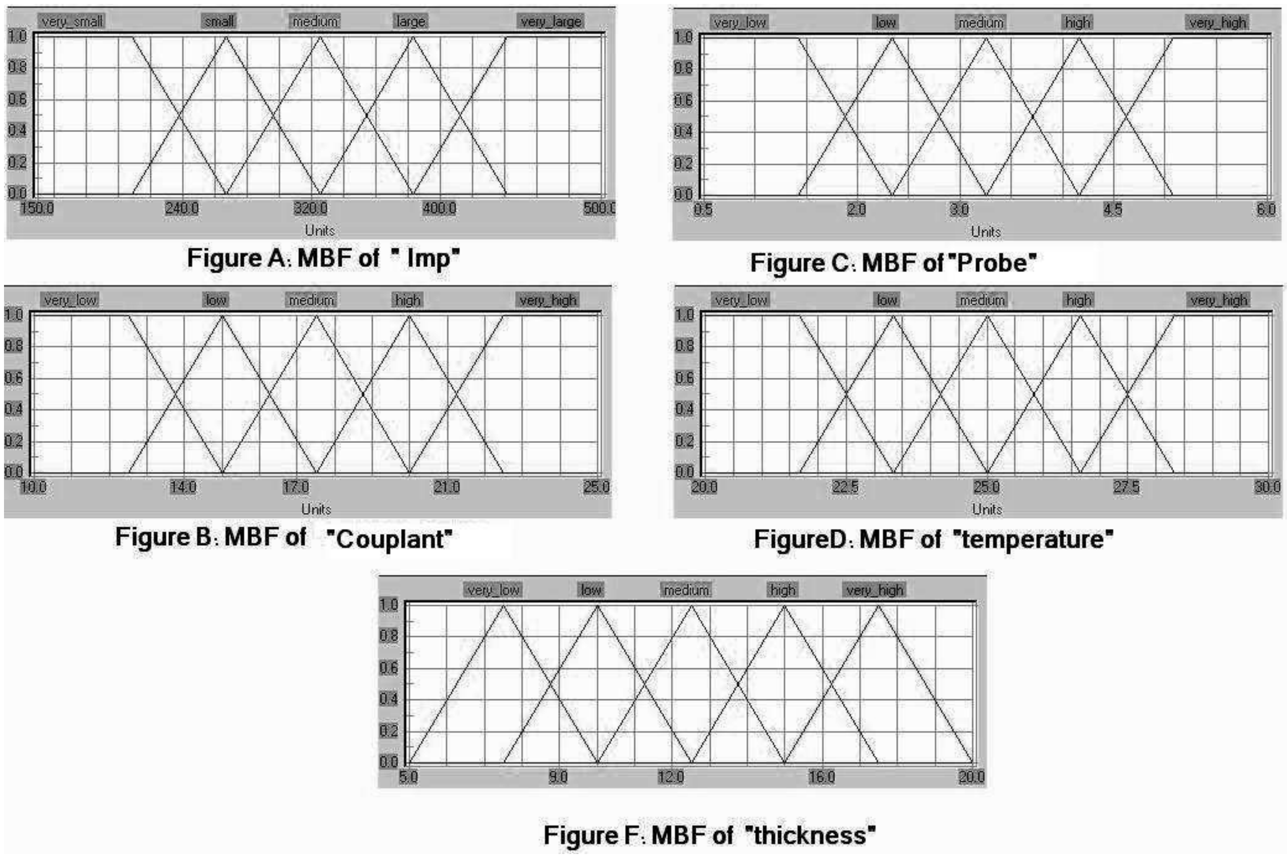


Figure3. Membership functions for fuzzy blocks; (A)Specimen's Acoustic Impedance, (B) Couplant's Acoustic Impedance, (C) Probe Frequency, (D) Circumstances' Temperature, (F) Specimen's Thickness

Fuzzy control rule and surface also is illustrated in Fig.4. The inputs are mapped into these membership functions and a degree of membership is found in how much of the inputs belong to that particular linguistic label. The membership can take on a value from zero to one for each of the linguistic labels. For each of the input and output variables, the following eight linguistic labels are assigned to the membership functions.Once the membership is found for each of the linguistic labels, an intelligent decision can be made as to what the output should be. The equivalent term in fuzzy logic controller is the rule. The typical rule in this study was written as follows:

IF the "Temperature" is large (L), AND the "Couplant" is high (H), THEN the "Thickness" is Medium(M).

Table1. Properties of applied materials [1]

Property / Material		Density ρ [g/cm^3]	Velocity of Longitudinal Sound Wave V_L [Km/s]	Acoustic Impedance $Z=\rho V_L * 10^4$ [g/cm^2.s]
Test Part	Aluminum	2.7	6.32	171
	Iron\NA-Steel	7.7	5.9	454.3
	Gray Cast Iron	7.8	4.8	374.4
	Copper	8.93	4.66	416.1
Couplant	Glycerin	1.26	1.92	24.2
	Water (20°C)	1.00	1.48	14.83
	Petroleum	0.825	1.29	10.7

In the case of determining the thickness at its desired recognition amount under varying inputs, rules are made for every combination of temperature and couplant type in order to minimize the error of recognition of thickness. After the rules are evaluated, each output membership function will contain a corresponding membership. The output will not move as smoothly from value to value as it would have if a more complicated defuzzification method was chosen, but the thickness advantages outweigh the small gain in accuracy in a real-time control situation where time response is a concern. The first step in establishing the algorithm for thickness diagnosis and its recognition strategy is the selection of appropriate shapes of fuzzy membership functions (or fuzzy sets) for the process variables. This is based upon experimental data and observed system behaviors. For any variable, such as the output (Thickness) with five linguistic levels, i.e. Very Low, Low, Medium, High and Very High, an overlap between any two adjacent levels (such as low and medium) is logical and acceptable; while an overlap between any two separate levels (such as very low and medium) is not acceptable. Triangular fuzzy sets have been designed to fuzzify the input variables such as acoustic impedance, temperature, etc. A trapezoid shape has been chosen to establish the fuzzy membership functions of output state. The relationship between inputs and outputs in a fuzzy system is characterized by a set of linguistic statements called *fuzzy rules*. After FLC results and rules were considered, the effects of incorporating the new system on the thickness recognition were simulated with MATLAB® software.

3. Results

The results of simulation for proposed evaluation strategy by FLC in recognition of thickness are tabulated in Table 2 – 4. Comparing actual values with acquired ones, it could be inferred that all mean errors are lower than *standard* deviation. On the other hand, the least error percentages belong to Copper (Cu) what we could guess from the beginning; because it has the most density from Table 1 and more homogeneous structure than others. In general, Gray Cast Iron and Aluminum have the least accuracy because of inhomogeneous structure and bigger grains for former and less density for the latter. Besides these issues, investigating the results for a specific specimen may imply that the denser the couplant is, the more accuracy we can obtain, as it might be guessed because in denser circumstances scattering of sound waves is lower and velocity of longitudinal sound waves is upper. Furthermore an intelligent system successfully evaluates the thickness of target parts not beyond a mean error of ٠.5% without regard to couplant material and consequently improves our speed and accuracy for measuring thickness.

Table2. Water as a Couplant Material

		Al	Iron/NA-St	GCI	Cu
Actual Thickness (mm)		12.00	12.00	12.00	12.00
Our Suggested UT (mm)		12.48	11.66	12.50	12.24
Mean Error (%)	30 °C	4.36	2.86	4.13	2.01
	25 °C	4.27	2.80	4.05	1.97
	20 °C	4.19	2.75	3.96	1.93

Table3. Petroleum as a Couplant Material

		Al	Iron/ NA-St	GCI	Cu
Actual Thickness (mm)		12.00	12.00	12.00	12.00
Our Suggested UT (mm)		12.39	11.74	12.46	12.21
Mean Error (%)	30 °C	3.21	2.14	3.82	1.71
	25 °C	3.15	2.10	3.74	1.68
	20 °C	3.08	2.05	3.67	1.64

Table4. Glycerin as a Couplant Material

		Al	Iron/ NA-St	GCI	Cu
Actual Thickness (mm)		12.00	12.00	12.00	12.00
Our Suggested UT (mm)		12.26	12.19	12.41	12.16
Mean Error (%)	30 °C	2.18	1.57	3.38	1.31
	25 °C	2.14	1.54	3.31	1.28
	20 °C	2.09	1.51	3.24	1.26

4. Conclusion

Fuzzy Logic provides a completely different, unorthodox way to approach a control problem. In this study, we designed and applied an intelligent fuzzy logic controller for thickness detection. The designed fuzzy logic controller has four inputs and one output. The number and complexity of rules depends on the number of input parameters that are to be processed and the number fuzzy variables associated with each parameter. The inputs were frequency of probe, couplant's acoustic impedance, object's acoustic impedance, and temperature. The output was the thickness, particularly for thin objects. The range of all of them was described. Because of immersion method, we preferred to utilize pulse-echo method. The results showed that the thicker the specimen is, the more accurate the thickness can be determined. Final experimental results imply that the designed system is able to control and measure the thickness of thin objects (5-20 mm) successfully within a rate of mean error of 0.5%. This fuzzy control system approach almost invariably leads to quicker, cheaper solutions in comparison to traditional control system. Future work aims to discover the underlying processes by which autonomous thickness detection can best select fuzzy rules for suppression.

5. References

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