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Fuzzy prediction and experimental verification of road surface cleaning rate by pure waterjets*

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Abstract: The cleaning parameters affecting cleaning rate using pure waterjets to clean road surface was researched. A mathematical model for predicting cleaning rate was established using fuzzy mathematical method. A fuzzy rule base characterizing the relationship between input and output parameters was built through experiments. The prediction of cleaning rate was achieved under the condition of given input parameters by rule-based fuzzy reasoning. The prediction results were analyzed through experimental verification.

Key words: Waterjets, Cleaning rate, Cleaning parameters, Fuzzy rule base
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INTRODUCTION

Waterjet cleaning technology is mainly achieved by an erosion process of high pressure water to remove coating materials. Louis and Schikorr (1982) identified deposits removed by high-speed waterjet cleaning as rust, oil, rubber, organics, etc., and investigated the relationship between the properties of the deposits and substrata. Summers (1982) investigated the correlation between the standoff distance, pressure and cleaning effectiveness. Saunders and Barton (1986) investigated the relationships between cleaning performance and operating parameters such as pressure, nozzle size, fan angle, standoff distance and traverse speed. A significant number of waterjet cleaning studies mostly involved just qualitative experimental studies of the process fundamentals (Meng *et al*., 1996; Meng and Geskin, 1998; Leu *et al*., 1998; Sohr and Thorpe, 1993; Xu and Summers, 1994; Shen *et al*., 1996), while insufficient attention was paid to the quality of waterjet cleaning.

Road surface cleaning is a special case of the application of waterjet cleaning technology and is very significant to the maintenance of the road surface and the prevention of environmental pollution. The road surface deposit mainly consists of carpolite, dust and their agglomeration. The surface of the substratum is extremely rough. There is mechanical adhesion between the deposit and the substratum, and thus the pressure needed by the deposit removal is low (Louis and Schikorr, 1982). At the same time, the needed standoff distance, width and nozzle traverse rate are larger than those used in conventional cleaning (Meng *et al*., 1996; Meng and Geskin, 1998; Leu *et al*., 1998; Sohr and Thorpe, 1993; Xu and Summers, 1994; Shen *et al*., 1996). Due to the width of the surface to be cleaned, a special cleaning vehicle is needed to install several nozzles working simultaneously to achieve the desired effect. Taggart *et al.*(2002a; 2002b) conducted ice cutting trials using high pressure waterjet for winter maintenance of pavement surfaces, but they needed field trials to put it into practice. There are only a few studies of the cleaning operations under these conditions.

The effectiveness of road cleaning in the final

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analysis is characterized by the cleaning rate, which is the crucial parameter of waterjet road cleaning. The accurate prediction of the rate of waterjet road cleaning is a base of the process optimization and its adoption in practice. The waterjet cleaning effectiveness is affected by waterpower parameters, working parameters, nozzle structural parameters, etc. Because the relationship between these parameters and the cleaning rate is highly nonlinear, it is impossible to precisely calculate and predict it using the traditional mathematical theories. However, the application of fuzzy logic enables us to address this issue (Babets and Geskin, 2000; Babets, 2001).

PARAMETERS AFFECTING ROAD SURFACE CLEANING

The effectiveness of road cleaning is defined as the ratio of well-cleaned area to the whole area in the cleaning process. The cleaning result is mainly affected by waterpower parameters, working parameters and nozzle structural parameters. In this paper, the type and size of the nozzle is given, thus the nozzle structural parameters will not be considered. So the parameters affecting cleaning rate are pressure (p), standoff distance (s), traverse rate (t) and the installation angle (a), as shown in Fig.1. Any change of any parameter will result in different cleaning rate. The relationships between the parameters and cleaning rate are linguistic information from experiments. For example, if pressure is 3.5 MPa, standoff distance is 270 mm, nozzle traverse rate is 70 m/min and the installation angle of the nozzle is 75°, the cleaning rate will be 71.7%. Increasing the pressure will lead to the increase of the cleaning rate, and decreasing standoff distance will also lead to the increase of the cleaning rate. These correlations reflect the affecting trend of the parameters on the cleaning rate, and they are nonlinear, and so cannot be modeled directly by mathematical equation. By using fuzzy logic, we use affecting parameters as input variables, and cleaning rate as output variable, and then establish a fuzzy rule base characterizing the relationships between input and output variables. By using rules reasoning and the defuzzification method, the cleaning rate can be predicted accurately for any input variables.

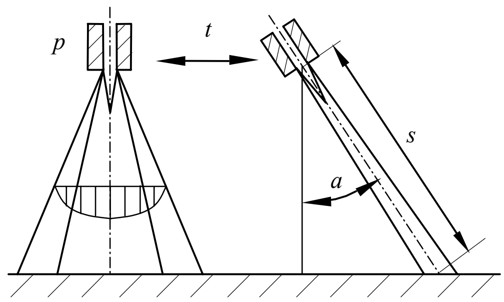

Fig.1 Main parameters influencing cleaning rate

DEGREE OF MEMBERSHIP FUNCTION OF INPUT AND OUTPUT VARIABLES

The first stage in the application of fuzzy logic to model the cleaning process is identifying the variation ranges of input and output variables. Then the range of each variable is divided into a group of fuzzy sets. Each fuzzy set is given a proper name and assigned a membership function. The fuzzy sets of input variables are set to different quantity according to the needs of experiments. The membership function is assigned without depending on the results of the experiments. There are some commonly used fuzzy distributions such as trapezoidal distribution, Gaussian distribution and Cauchy distribution (Lu and Gong, 2002). Because the expression and calculation of trapezoidal distribution is simple and easy, so the trapezoidal distribution is used to assign the degree of membership function for the input and output variables.

1. Pressure (p)

The pressure range of 0 to 10 MPa can be divided into four fuzzy sets as {Low, Medium, High, Very High} and is $\boldsymbol{P}=\{\boldsymbol{P}_1, \boldsymbol{P}_2, \boldsymbol{P}_3, \boldsymbol{P}_4\}$ expressed in vector form. The degree of membership function of pressure is shown in Fig.2.

The membership function of pressure in equation form is listed as follows:

$$p_1(x)=\frac{5-x}{2.5},\ x\in[2.5,5] \tag{1}$$

$$p_2(x)=\begin{cases}\dfrac{x-2.5}{2.5}, & x\in[2.5,5]\\[2mm] \dfrac{7.5-x}{2.5}, & x\in[5,7.5]\end{cases} \tag{2}$$

$$p_3(x)=\begin{cases}\dfrac{x-5}{2.5}, & x\in[5,7.5]\\ \dfrac{10-x}{2.5}, & x\in[7.5,10]\end{cases} \quad (3)$$

$$p_4(x)=\frac{x-7.5}{2.5}, \quad x\in[7.5,10] \quad (4)$$

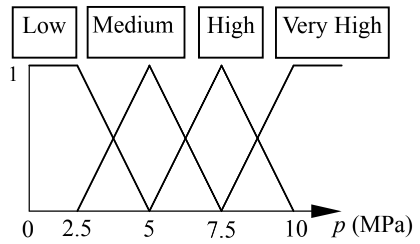

Fig.2 Membership function of pressure

2. Standoff distance (s)

The range of standoff distance is 0 to 400 mm and is divided into four fuzzy sets as {Short, Medium, Large, Very Large}. It is $\boldsymbol{S}$={$\boldsymbol{S}_1$, $\boldsymbol{S}_2$, $\boldsymbol{S}_3$, $\boldsymbol{S}_4$} expressed in vector form. The membership function of standoff distance is shown in Fig.3.

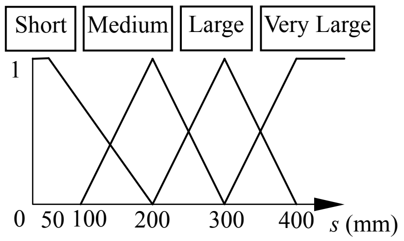

Fig.3 Membership function of standoff distance

3. Traverse rate (t)

The range of traverse rate is 0 to 120 m/min and is divided into five fuzzy sets as {Very Low, Low, Medium, High, Very high}. It is $\boldsymbol{T}$={$\boldsymbol{T}_1$, $\boldsymbol{T}_2$, $\boldsymbol{T}_3$, $\boldsymbol{T}_4$, $\boldsymbol{T}_5$} expressed in vector form. The membership function of traverse rate is shown in Fig.4.

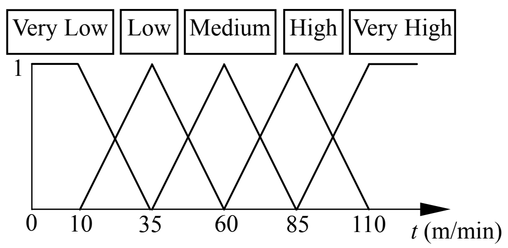

Fig.4 Membership function of traverse rate

4. Installation angle of the nozzle (a)

The range of installation angle is 0° to 90° and is divided into three fuzzy sets as {Small, Medium, Large}. It is $\boldsymbol{A}$={$\boldsymbol{A}_1$, $\boldsymbol{A}_2$, $\boldsymbol{A}_3$} expressed in vector form. The membership function of the installation angle is shown in Fig.5.

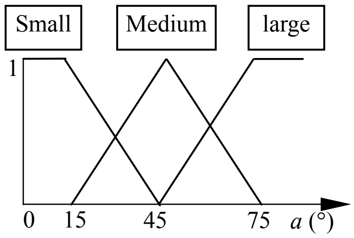

Fig.5 Membership function of installation angle

5. Output variable (cr)

The more the fuzzy sets of the output variable, the nearer is the prediction value to the real value. As output variable, the cleaning rate range from 0 to 100% and is divided into nine fuzzy sets as {Extremely Low, Very Low, Low, Medium, Less High, High, Very High, Very Very High, Extremely High}. It is $\boldsymbol{R}$={$\boldsymbol{R}_1$, $\boldsymbol{R}_2$, $\boldsymbol{R}_3$, $\boldsymbol{R}_4$, $\boldsymbol{R}_5$, $\boldsymbol{R}_6$, $\boldsymbol{R}_7$, $\boldsymbol{R}_8$, $\boldsymbol{R}_9$} expressed in vector form. The membership function of cleaning rate is shown in Fig.6.

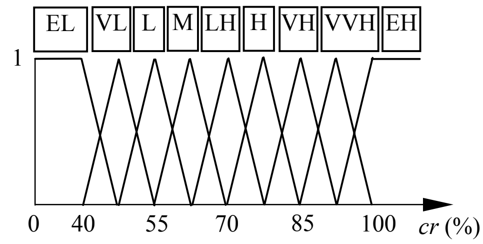

Fig.6 Membership function of cleaning rate

ESTABLISHING THE FUZZY RULE BASE OF INPUT AND OUTPUT VARIABLES

Determining of the relationship between input and output variables

In order to determine the relationship between input and output variables, orthogonal experiments on road cleaning were conducted by varying the value of affecting parameters of pressure, standoff distance, traverse rate and installation angle. The values of each parameter used in the experiments were set to the value when parameter membership degree is 1. For example, the fuzzy sets of pressure are {Low, Medium, High, Very high}. When the degree of membership is equal to 1, the corresponding pressure will be {2.5 MPa, 5 MPa, 7.5 MPa, 10 MPa}. These pressure values will be used in experiments. In this way, the standoff distance is {50 mm, 200 mm, 300 mm, 400 mm}, the traverse rate is {10 m/min, 35 m/min, 60 m/min, 85 m/min, 110 m/min} and installation angle is {15°, 45°, 75°} for the experiments. So the total number of orthogonal experiments will be 4×4×5×3=240.

Each experiment will result in a cleaning rate, which should be determined to belong to which fuzzy sets of the output variable. So the value of the cleaning rate should be put into the membership function of the output variable to calculate its degree of membership. Then they will be identified to belong to which fuzzy sets using the principle of maximum degree of membership. For instance, if the pressure is 5 MPa, standoff distance is 300 mm, traverse rate is 60 m/min and installation angle is 45°, the cleaning rate will be 86% according to experiment. The degree of membership of cleaning rate is (86−85)/(92.5−85) =0.13 for fuzzy set "Very Very High", while the degree of membership is (92.5−86)/(92.5−85)=0.87 for fuzzy set "Very High". So it can be inferred that the cleaning rate belongs to the fuzzy set "Very High". According to the procedure above, one orthogonal experiment will create one relationship between input and output variable, that is $\boldsymbol{P}_2, \boldsymbol{S}_3, \boldsymbol{T}_2, \boldsymbol{A}_2 \rightarrow \boldsymbol{R}_7$.

Establishment of fuzzy rule base

The relationship between input and output variables described above is defined as fuzzy rule. One experiment results in one fuzzy rule. If all the fuzzy rules are saved in a database, a fuzzy rule base will be established. The number of rules in a fuzzy rule base is determined by the quantity of fuzzy sets of input parameters. So, the more the fuzzy sets of input parameters, the more the fuzzy rules. Fuzzy rules can be expressed by:

$$F(\boldsymbol{P}_i, \boldsymbol{S}_j, \boldsymbol{T}_k, \boldsymbol{A}_l) \rightarrow \boldsymbol{R}_x\ (i\in[1,4],\ j\in[1,4],\ k\in[1,5],\ l\in[1,3],\ x\in[1,9];\ i, j, k, l, x\in Z) \quad (5)$$

Fuzzy rule base is expressed in Fig.7.

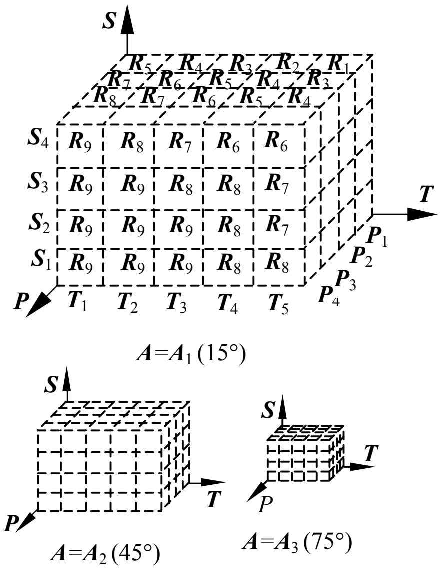

Fig.7 Expression of fuzzy rule base

PREDICTION OF CLEANING RATE

Combination and treatment of fuzzy rules

According to the definition of membership function, an input parameter has two degrees of memberships to two different fuzzy sets at most, which means one input parameter to two possible fuzzy sets. So the maximum number of fuzzy rules for a cleaning process will be:

$$N=2^n \quad (6)$$

N is number of fuzzy rules; n is number of input parameters; in this paper, there are four input parameters, so $N=2^4=16$.

Then the corresponding fuzzy sets of all input parameters should be combined to form fuzzy rules. Each group of combined fuzzy sets of input parameters will lead to a fuzzy set of output parameters. So, for any given input parameter, the first step is to identify its fuzzy sets and degree of membership, then combine the fuzzy sets to form a group of fuzzy rules (16 rules maximum). For each rule, there will be a fuzzy set of output variables.

For each fuzzy set of the output variables, because the degree of membership of input parameter may not be 1, so the degree of membership of output parameter may not be 1 also. To determine the output variable's degree of membership, the method of selecting the input parameters' minimum membership degrees is used, expressed as follows:

$$F_m(X)=\min\{\boldsymbol{P}_i(p), \boldsymbol{S}_j(s), \boldsymbol{T}_k(t), \boldsymbol{A}_l(a)\} \quad (7)$$

$F_m(X)$ is membership degree of the output variable; $\boldsymbol{P}_i(p)$, $\boldsymbol{S}_j(s)$, $\boldsymbol{T}_k(t)$, $\boldsymbol{A}_l(a)$ are membership degrees of input parameters p, s, t, a to fuzzy sets $\boldsymbol{P}_i$, $\boldsymbol{S}_j$, $\boldsymbol{T}_k$, $\boldsymbol{A}_l$.

Because the minimum membership degree of the input parameters is chosen as the membership degree of the output parameter, there must be such fuzzy sets whose membership degree is comparatively very small in all the rules of output parameters. The prediction value of this kind of fuzzy sets is far from the actual value of the output parameter. If they were taken into account, the prediction error will be enlarged. To avoid this problem, we use a parameter λ-*cut* to cut off those output fuzzy sets whose membership degrees are very small.

$$R(x)\geq\lambda\text{-}cut \quad (8)$$

The value that is smaller than λ-*cut* will be omitted, and the rest of the rules are adopted for the prediction of the output variable.

The prediction of output variable

For rules treated by λ-*cut* parameter, the defuzzification method of centroid method is adopted to predict the cleaning rate (Werner and Etienne, 1999), as shown in Eq.(9).

$$cr=\sum_{x\min}^{x\max} x\cdot A(x) \bigg/ \sum_{x\min}^{x\max} A(x) \quad (9)$$

EXPERIMENTAL VERIFICATION AND ANALYSIS

To verify the correctness of the fuzzy prediction method of cleaning rate, experiments were conducted to get the actual values of cleaning rate to compare with the predicted ones. The principle of the experiment is shown in Fig.8. A water system which consisted of water tank, water pump, pressure controller and fan-shaped nozzle was installed in a cleaning vehicle. Water flows from the water tank, through the water pump and pressure controller, then to the fan-shaped nozzle and impinges on the road. The pressure of the water could be controlled by the pressure controller. At the same time, the cleaning vehicle runs at the speed of t (traverse rate) to complete the cleaning process. The calculation of the cleaning rate was achieved by an image processing process. The principle of this process is to make the color of the substrata different from the deposits, then take photographs of the surface after cleaning, using image processing to calculate the cleaning rate (Hao and Zhang, 2001; Yoshio and Norikazu, 1995).

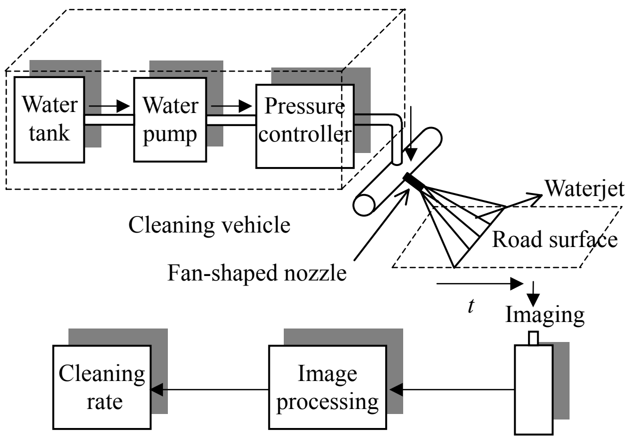

Fig.8 Principle of the experiment

Fig.9 compares predicting values and the verification values of the cleaning rate when the installation angle a is 45°, standoff distance s is 300 mm, and traverse rate t is 110 mm/min. It can be seen from the figure that, when the pressure was 2.5, 5, 7.5 MPa, the actual cleaning rate calculated from the experiment was 56.5%, 78.3% and 96% respectively. By using fuzzy logic method, the cleaning rates were predicted at the pressure of 2, 3, 4, 6, 7 MPa. At the same time, experiments were conducted to calculate the actual cleaning rates for the verification. The results showed that the largest relative error was 4.9% at pressure of 6 MPa. This value was regarded as enough for the accurate prediction of road cleaning. With fuzzy logic method, we can predict the cleaning rate at any value of the cleaning parameters. The accuracy of prediction depends on the number of fuzzy sets of the input and output variables, the number of experiments conducted and the selection of cut off parameter λ-*cut*. In the process of prediction, the intervals of the pressure could be shortened to a certain limit that the predicted values could be regarded as continuous. In this way, a continuous fitting curve could be derived from the predicted values, shown in Fig.10. This curve is significant for the optimization of the cleaning process.

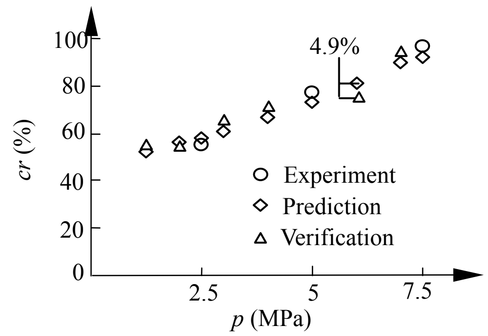

Fig.9 Comparison of results

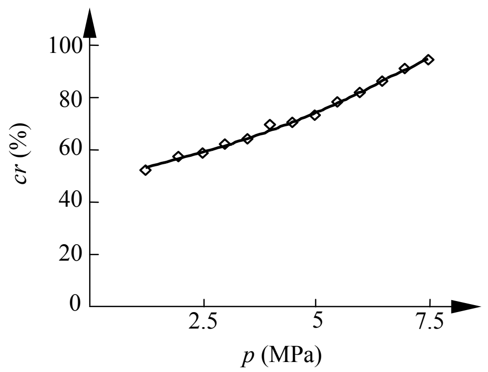

Fig.10 Fitting curve of predicted value

It can be seen from the verification results that fuzzy logic is a very useful method for predicting the cleaning rate. Because the correlations between waterjet cleaning parameters and cleaning effects are nonlinear, which can only be expressed by discreet experimental data points, by using fuzzy logic and its reasoning method, we can easily obtain the fitting curves of the input variables and cleaning rates. With these curves characterizing the relationships between cleaning parameters and cleaning rates, a foundation for optimizing of the cleaning quality of road surface cleaning was obtained.

CONCLUSION

A method of predicting the cleaning rate using fuzzy logic to model the cleaning process is put forward. Through experimental verification, the error between the prediction value and the actual value of the cleaning rate is within 5%, which is enough for the requirements of precise prediction. The prediction method provided a basis for optimizing the parameters of road surface cleaning. Because the parameters affecting the general quality of road surface cleaning consists of cleaning rate and other appraisal parameters such as production rate, water consumption and energy consumption, the precise prediction of the cleaning rate formed a base for the optimized configuration of the cleaning parameters to reach the best cleaning effects.

APPENIX: AN EXAMPLE OF USING FUZZY PREDICTION METHOD

According to the cleaning rate prediction method mentioned above, we can predict the cleaning rate for any input parameters. For example, the input pressure (p) is 4 MPa, standoff distance (s) is 230 mm, traverse rate (t) is 90 m/min, and installation angle (a) is 45°. The process is implemented by:

(1) Calculating the membership degrees of input parameters:

$$\boldsymbol{P}_1(4)=0.4,\quad \boldsymbol{P}_2(4)=0.6;$$
$$\boldsymbol{S}_2(230)=0.7,\quad \boldsymbol{S}_3(230)=0.3;$$
$$\boldsymbol{T}_4(90)=0.8,\quad \boldsymbol{T}_5(90)=0.2;$$
$$\boldsymbol{A}_2(45)=1.$$

(2) Combining fuzzy rules.

According to the fuzzy rule base established by Eq.(5), we can reason that there are 8 results:

$$F(\boldsymbol{P}_1, \boldsymbol{S}_2, \boldsymbol{T}_4, \boldsymbol{A}_2)\rightarrow\boldsymbol{R}_6;\quad F(\boldsymbol{P}_1, \boldsymbol{S}_2, \boldsymbol{T}_5, \boldsymbol{A}_2)\rightarrow\boldsymbol{R}_5;$$
$$F(\boldsymbol{P}_1, \boldsymbol{S}_3, \boldsymbol{T}_4, \boldsymbol{A}_2)\rightarrow\boldsymbol{R}_6;\quad F(\boldsymbol{P}_1, \boldsymbol{S}_3, \boldsymbol{T}_5, \boldsymbol{A}_2)\rightarrow\boldsymbol{R}_4;$$
$$F(\boldsymbol{P}_2, \boldsymbol{S}_2, \boldsymbol{T}_4, \boldsymbol{A}_2)\rightarrow\boldsymbol{R}_8;\quad F(\boldsymbol{P}_2, \boldsymbol{S}_2, \boldsymbol{T}_5, \boldsymbol{A}_2)\rightarrow\boldsymbol{R}_7;$$
$$F(\boldsymbol{P}_2, \boldsymbol{S}_3, \boldsymbol{T}_4, \boldsymbol{A}_2)\rightarrow\boldsymbol{R}_7;\quad F(\boldsymbol{P}_2, \boldsymbol{S}_3, \boldsymbol{T}_5, \boldsymbol{A}_2)\rightarrow\boldsymbol{R}_6.$$

(3) Determining the membership degree of output variable.

$F_1(X)=\min\{\boldsymbol{P}_1(4),\ \boldsymbol{S}_2(230),\ \boldsymbol{T}_4(90),\ \boldsymbol{A}_2(45)\}$ $=\min(0.4,0.7,0.8,1)=0.4$;

$F_2(X)=\min\{\boldsymbol{P}_1(4),\ \boldsymbol{S}_2(230),\ \boldsymbol{T}_5(90),\ \boldsymbol{A}_2(45)\}$ $=\min(0.4,0.7,0.2,1)=0.2$;

$F_3(X)=\min\{\boldsymbol{P}_1(4),\ \boldsymbol{S}_3(230),\ \boldsymbol{T}_4(90),\ \boldsymbol{A}_2(45)\}$

=min(0.4,0.3,0.8,1)=0.3;

$F_4(X)$=min{$\boldsymbol{P}_1(4)$, $\boldsymbol{S}_3(230)$, $\boldsymbol{T}_5(90)$, $\boldsymbol{A}_2(45)$} =min(0.4,0.3,0.2,1)=0.2;

$F_5(X)$=min{$\boldsymbol{P}_2(4)$, $\boldsymbol{S}_2(230)$, $\boldsymbol{T}_4(90)$, $\boldsymbol{A}_2(45)$} =min(0.6,0.7,0.8,1)=0.6;

$F_6(X)$=min{$\boldsymbol{P}_2(4)$, $\boldsymbol{S}_2(230)$, $\boldsymbol{T}_5(90)$, $\boldsymbol{A}_2(45)$} =min(0.6,0.7,0.2,1)=0.2;

$F_7(X)$=min{$\boldsymbol{P}_2(4)$, $\boldsymbol{S}_3(230)$, $\boldsymbol{T}_4(90)$, $\boldsymbol{A}_2(45)$} =min(0.6,0.3,0.8,1)=0.3;

$F_8(X)$=min{$\boldsymbol{P}_2(4)$, $\boldsymbol{S}_3(230)$, $\boldsymbol{T}_5(90)$, $\boldsymbol{A}_2(45)$} =min(0.6,0.3,0.2,1)=0.2.

(4) Cut-off Treatment.

Set *λ-cut*=0.3, those rules whose degree of membership is smaller than *λ-cut* are cut off. We get:

$F_1(X)$=0.4; $F_3(X)$=0.3; $F_5(X)$=0.6; $F_7(X)$=0.3.

The result is shown in Fig.11.

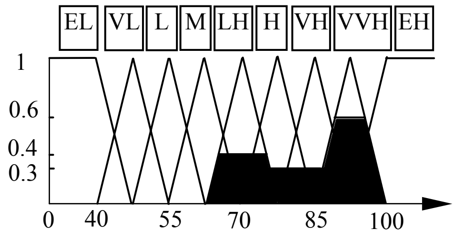

Fig.11 Cleaning rate (%)

(5) Cleaning rate prediction

The centroid defuzzification method can be used to get the prediction value of the cleaning rate as:

cr=82.2%.

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