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Multi-objective genetic algorithm for the optimization of road surface cleaning process*

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Abstract: The parameters affecting road surface cleaning using waterjets were researched and a fuzzy neural network method of calculating cleaning rate was provided. A genetic algorithm was used to configure the cleaning parameters of pressure, standoff distance, traverse rate and angle of nozzles for the optimization of the cleaning effectiveness, efficiency, energy and water consumption, and a multi-objective optimization model was established. After calculation, the optimized results and the trend of variation of cleaning effectiveness, efficiency, energy and water consumption in different weighting factors were analyzed.

Key words: Optimization, Waterjets, Road surface cleaning, Genetic algorithm, Multi-objective
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INTRODUCTION

The technology of using waterjet for cleaning is an important problem in engineering. There are many researches on using waterjets for cleaning. Most of them are focused on the relationship between cleaning parameters and cleaning effectiveness (Louis and Schikorr, 1982; Summers, 1982; Liu *et al*., 1999; Taggart *et al*., 2002). However, few researches are related to the optimization of cleaning parameters to improve cleaning performance even if it is very crucial for fully utilizing the cleaning ability of waterjets and saving energy and resources. Babets and Geskin (2000) studied the energy consumption in high pressure cleaning. Genetic algorithm (GA) was used for the optimization of cleaning parameters to obtain the best energy used in paint cleaning process. But, only energy consumption was considered since the objective for optimizing is multiple. In this work, the multi-objective optimizing methods of configuring cleaning parameters for the optimization of cleaning effectiveness, cleaning production rate, energy and water consumption in the process of using waterjet for cleaning of road surface were investigated.

PARAMETERS AFFECTING SURFACE CLEANING

Road surface cleaning is a special case of the application of waterjet cleaning technology and is very important for the maintenance of road surface and the prevention of environmental pollution. The layer of road surface mainly consists of carpolite, dust, smear and their agglomeration. The interaction between layer and substratum is mechanical adhesion, the degree of which is very low (Louis and Schikorr, 1982). At the same time, the cleaning operation needs to clean large area in comparatively short time at high traverse rate. So the characters of nozzle type, pressure, standoff distance, traverse rate, etc. of road surface cleaning are different from high-pressure waterjet cleaning (Xu and Summers, 1994; Shen *et al*., 1996), and also different from ice cutting for winter maintenance of road surfaces (Taggart *et al*., 2002).

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The parameters affecting the road surface cleaning are mainly composed of pressure (P), standoff distance (S), traverse rate (T) and the installation angle (A), as shown in Fig.1. P, S and A mainly determine the impact force delivered to the surface, while T is responsible for the energy acting on the surface. The effectiveness of waterjet cleaning, which means the degree of neatness of the road cleaned, expressed by cleaning rate, is defined as the ratio of clean area to the whole cleaning area in the process of road surface cleaning. The cleaning efficiency, expressed by the production rate, is defined as the cleaning area in unit time. Energy consumption is defined as the energy used in cleaning unit area. Water consumption is defined as the water used in cleaning unit area.

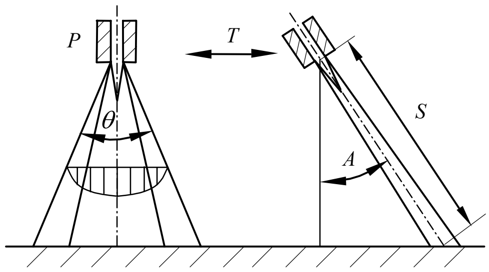

Fig.1 Main parameters affecting cleaning quality

The problem of how to configure the cleaning parameters in road surface cleaning process to optimize the cleaning effectiveness, efficiency, energy and water consumption is a typical multi-objective optimization problem. The relationships between the objectives for optimization and the variables are non-linear. GA is an effective method for this kind of problems.

OPTIMIZATION MODEL OF ROAD SURFACE CLEANING

The objective of optimizing the cleaning parameters is to acquire the highest cleaning rate and production rate at the lowest water consumption and expenditure of energy. So the dependent variables are cleaning pressure P, standoff distance S, traverse rate T and nozzle angle A.

Cleaning rate

The relationship between the cleaning rate (R_c) and cleaning parameters was obtained from experiments. About 111 sets of experiments were conducted using different cleaning parameters. The experiments showed that the relationship between the cleaning rate and the cleaning parameters were nonlinear. The use of conventional mathematical method cannot model the relationship between the cleaning parameters and cleaning rate, while AI technology provide an effective way for solving this kind of problem. Adaptive neural-fuzzy inference system (ANFIS), first introduced by Jang (1993), was a proper method for modelling the relationship between the cleaning parameters and cleaning rate, and predicting the cleaning rate at any cleaning parameter.

The ANFIS used in this paper was based on Takagi-Sugeno inference model and its architecture consists of five layers: fuzzy layer, product layer, normalized layer, defuzzification layer, output layer. The combination of the least-square method and back propagation gradient descent method was used for the training of membership function parameters to emulate the given training dataset. A total of 111 experimental datasets from the 111 sets of experiments were used for the ANFIS. Among them, 81 datasets were used as training sets to set up the cleaning rate prediction model; the remaining 30 datasets were used as testing data to verify the accuracy of the prediction model. The variation range of the parameters was: P: 2~4 MPa; T: 50~110 m/min; S: 150~350 mm; A: 30°~60°. Triangular membership functions were used for the cleaning parameters of P, T, S and A. The fuzzy sets of cleaning parameters were divided into two sub sets: SMALL and LARGE. The fuzzy architecture of ANFIS is shown in Fig.2. Sixteen fuzzy rules could be generated after the training according to the setting. The trained triangular membership functions are shown in the figure. After training in MATLAB, the cleaning rate at given cleaning parameters can be calculated by its evalfis function.

Production rate

Production rate (R_p) is expressed by the cleaning area of the waterjets in unit time. The cleaning area of a nozzle is the product of waterjet width and traverse length, and is different from the clean area which is the clean part of the whole cleaning area. R_p is expressed as:

$$R_p=2STN_1\tan(\theta/2). \quad (1)$$

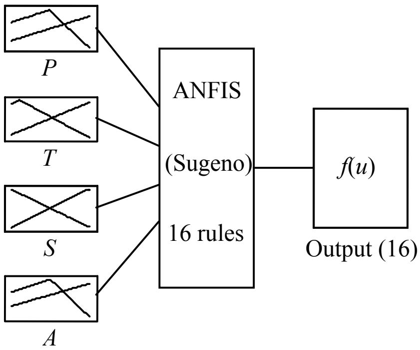

Fig.2 Fuzzy architecture of ANFIS

Energy consumption

Energy consumption (E) is the energy consumed in cleaning unit area, and is expressed as:

$$E=\frac{\pi c_D D^2(2P/\rho_w)^{1/2}}{8ST\tan(\theta/2)}P. \quad (2)$$

Water consumption

Water consumption (Q) is the water consumed in cleaning unit area, and is expressed as:

$$Q=\frac{\pi c_D D^2(2P/\rho_w)^{1/2}}{8ST\tan(\theta/2)}. \quad (3)$$

Objective function

In order to overcome the large differences in numerical values between the sub objectives, normalization of each sub-objective is introduced. The resultant weighted objective function (F) to be minimized here is:

$$F=w_1\frac{C}{C^*}+w_2\frac{R_p}{R_p^*}-w_3\frac{E}{E^*}-w_4\frac{Q}{Q^*}+F_0, \quad w_1+w_2+w_3+w_4=1. \quad (4)$$

GA OPTIMIZATION PROCESS

Genetic algorithms (GAs) are search algorithms based on concepts of natural selection and natural genetics. The searching process simulates the natural evaluation of biological creatures to solve optimization problems. Generally, there are four main steps in the GA optimization process: coding, reproduction, crossover and mutation.

Coding is the process of changing variable to chromosome. According to the variation range and precision requirements of the variables, 5 bits were chosen for P, 6 bits were chosen for T and A and 8 bits were chosen for S. Decoded value is calculated according to Eq.(5):

$$X_{dec}=X_{min}+X_{bin}\cdot\frac{X_{max}-X_{min}}{2^n-1}. \quad (5)$$

Reproduction is the process in which individual strings are copied according to their fitness function. In this paper, the rank selection method is used (Baker, 1985). In rank selection, individuals are assigned fitness according to their rank in the population. One variable, P_s, is used to determine the selective pressure. The fitness of the others is determined by

$$f(x_i)=2-P_s+2(P_s-1)\frac{x_i-1}{N-1}. \quad (6)$$

Then the probability of reproduction selection p_{si} of an individual i being selected is given by

$$p_{si}=f_i\bigg/\sum_{i=1}^{n}f_i. \quad (7)$$

First, individuals in the population are ranked in increasing order according to their objective function values. Then the fitness value of each individual is calculated using Eq.(6). According to Eq.(7), p_{si} of each individual can be determined. Roulette wheel parent selection is used for reproduction of chromosome. By using rank selection method, when the fitness variance is high, P_s can be reduced to avoid multi-selection of individuals whose fitness is high.

When the fitness variance is low, selection can be adjusted by increasing P_s. By calculation, the selection pressure P_s is selected as 1.6.

Crossover is the process of exchanging useful blocks between two strings to create new strings that preserve the best material from the parent strings. The number of strings in which material is exchanged is controlled by the crossover probability p_c. Two-point crossover is used in this work. In this paper, p_c is set to 0.9.

Mutation is randomly applied with low probability, and modifies elements in the chromosomes. The role of mutation is to serve as a safety net to recover good genetic material which may be lost through the action of selection and crossover. The probability of mutation p_m is selected as 0.005 in this paper.

OPTIMIZATION RESULT ANALYSIS

The input data for this optimization problem are shown in Table 1.

The processing variables for the optimization were obtained according to the experiments. That is, P ranged 2~4 MPa, R_c ranged 50~110 m/min, S ranged 150~350 mm and A ranged 30°~60°. The results of the calculations performed for several numbers of chromosomes in the population and weighting factors are presented in Table 2. The determination of weighting factors is related to which item of the objects is emphasized. So they should be allocated according to the practical application and the user's experience. In Table 3, a series of weighting factors were allocated in increasing order of w_1 and w_2 in Rows 1~6 to show the variation of the optimizing parameters and objectives.

Table 1 Parameters used in the optimization process

Parameter	Value	Unit	Parameter	Value	Unit
θ	45	deg (°)	E^*	4273	J/m^2
N_1	15	–	Q^*	1.068	L/m^2
c_D	0.7	–	F_0	1	–
D	0.0015	m	N	30, 50, 100	
ρ_w	1000	kg/m^3	P_c	0.9	
C^*	1	–	P_s	1.6	
R_p^*	8	m^2/s	P_m	0.005	

*: the maximum

Table 3 Distribution of weighting factors

Row	w_1	w_2	w_3	w_4
1~3	0.1	0.1	0.4	0.4
4	0.2	0.2	0.3	0.3
5	0.3	0.3	0.2	0.2
6	0.4	0.4	0.1	0.1
7	0.4	0.3	0.15	0.15

In Table 2, Rows 1~3 were calculated using the same weighting factors and 30, 50, and 100 chromosomes respectively. It can be seen that, for these three rows, the optimal values of the independent variables and components of the fitness are nearly the same. So, a population of 30 chromosomes was used for the calculations of Rows 4~7.

It can be seen from the optimized results of Rows 3~6 that, when the weighting factor of cleaning rate, w_1, and that of production rate, w_2, are both increased from 0.1 to 0.4, the optimized independent variable of pressure P increased gradually from 2 to 4 MPa, and that the product of $S{\cdot}T$ increased from 16500 to 21250 mm·m/min. This variation trend is consistent with the definition of the optimization objectives. When w_2 is increased, the requirement for

Table 2 Optimizing results in different weighting factors

No.	Sample scale	P (MPa)	S (mm)	T (m/min)	A (°)	R_c (m/min)	R_p (m^2/s)	E (J/m^2)	Q (L/m^2)	Objective function
1	30	2.0	151	109	42.2	0.251	3.41	688.5	0.34	0.875
2	50	2.0	152	110	41.5	0.298	3.46	677.8	0.33	0.879
3	100	2.1	150	110	42.3	0.255	3.42	686.8	0.33	0.876
4	30	2.2	160	110	41.5	0.288	3.64	742.8	0.34	1.000
5	30	2.8	200	95	40.6	0.376	3.94	988.0	0.35	1.140
6	30	4.0	250	85	44.1	0.750	4.40	1508.0	0.38	1.450
7	30	3.6	172	96	43.1	0.710	3.41	1657.0	0.46	1.290

R_p becomes emphasized, i.e., R_p increases (from 3.42 to 4.40 m^2/s). According to Eq.(1), the product of $S \cdot T$ increases with R_p. At the same time, w_3 and w_4 are decreased, which means the requirement for energy and water consumption becomes weak, so E and Q will increase correspondingly. According to Eqs.(2) and (3), the pressure P increases with increase of $S \cdot T$ to ensure the increase of E and Q. With increase of w_1, R_c increases (from 0.25 to 0.75); but R_c will decrease with the increase of $S \cdot T$. To ensure R_c increases in the end, the cleaning pressure P will increase faster than $S \cdot T$ to ensure the increase of R_c. Nozzle angle A is a parameter related only to R_c, so the variation of A is just a kind of regulation to compensate for the variation of R_c caused by the variation of P, S and T.

According to the requirement of cleaning effectiveness, the acceptable R_c should be greater than 0.7, which means the weighting factor w_1 should be greater than 0.4. At the same time, R_p is more important than energy expenditure and water consumption, so its weighting factor is comparatively large. Appropriate weighting factors configuration of w_1=0.4, w_2=0.3, w_3=0.15, w_4=0.15 in Row 7 is suggested for practical applications. The optimized objective is: R_c=0.71 (m/min), R_p=3.41 m^2/s, E=1657 J/m^2, Q=0.46 L/m^2. The optimized parameter is: P=3.6 MPa, S=172 mm, T=96 m/min A=43.1°. Because of the multiple objectives for optimization, there are many solutions for the problem according to the difference of weighting factors. So the suggestion is reasonable but not the only choice.

CONCLUSION

The ANFIS prediction method was successfully used for predicting cleaning rate as a sub-objective for optimization. Genetic algorithms (GAs) were used for multi-objective optimization of road surface cleaning rate, production rate, energy expenditure, and water consumption. Useful cleaning parameters datasets were put forward. Optimization results showed that the variation trends of the optimized parameters are consistent with the optimizing objectives definition. When non-linear optimizing objective cannot be modelled by multi-objective optimization, the combination of ANFIS and genetic algorithms provided an effective method for the optimization. The optimization method and configuration of weighting factors provide a useful way for the optimization of road surface cleaning parameters to make full use of the waterjet cleaning potentials.

Nomenclature

Parameter	Meaning	Parameter	Meaning
A	Nozzle angle (°)	R_p^*	Limit of R_p (m^2/s)
C^*	Limit of R_c	Q	Water consumption (L/m^2)
c_D	Coefficient of flow	Q^*	Limit of Q (L/m^2)
R_c	Cleaning rate (m/min)	S	Standoff distance (mm)
D	Nozzle diameter (m)	P_s	The selective pressure
E^*	Limit of Energy (J/m^2)	T	Traverse rate (m/min)
f	Fitness value	w_1	Weight factor of R_c
F_0	Amendment value	w_2	Weight factor of R_p
n	Number of bits coded	w_3	Weight factor of Energy
N	Population size	w_4	Weight factor of Q
N_1	Number of nozzles	X_{bin}	Binary coding value of variable
P	Cleaning pressure (MPa)	X_{dec}	Decoded value of variable
p_c	Probability of crossover	x_i	Position in the ordered population of individual
p_m	Probability of mutation	X_{max}	Maximum value of variable
p_{si}	Probability of selection	X_{min}	Minimum value of variable
R_p	Production rate (m^2/s)	θ	Flare angle of nozzle (°)

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