

An adaptive network-based fuzzy approach for prediction of surface roughness in CNC end milling

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Received 26 May 2005; accepted 30 January 2006

An Adaptive Network-based Fuzzy Inference System (ANFIS) has been designed for modeling and predicting the surface roughness in end milling operation for set of three given milling parameters (spindle speed, feed rate and depth of cut). Two different membership functions (triangular and bell shaped) were used during the hybrid-training process of ANFIS in order to compare the prediction accuracy of surface roughness by the two membership functions. The predicted surface roughness values obtained from ANFIS were compared with experimental data and multiple regression analysis. The comparison indicates that the adoption of both membership functions in ANFIS achieved better accuracy than multiple regression model.

Keywords: Adaptive Network, End milling, Fuzzy system, Surface roughness

IPC Code: G06N7/02; G01B5/28

Introduction

Modeling and prediction of surface roughness (SR) of a workpiece in end milling play an important role in modern automated manufacturing industry. Alauddin *et al*¹ developed mathematical polynomial models for SR in terms of cutting speed, feed and axial depth of cut for end milling of steel. Lou *et al*² studied the effect of spindle speed, feed and depth of cut on the SR of end milling process. Response Surface Methodology³ was successfully applied for SR modeling of difficult to machine materials (EN32). Tsai *et al*⁴ used in process surface recognition system based on neural networks in end milling operation. An adaptive neuro-fuzzy inference system⁵ was developed for predicting SR in turning operation. Dweiri *et al*⁶ used neural-fuzzy system to model SR of Aluminic-79 workpiece in CNC down milling. This study attempts to design Adaptive Network-based Fuzzy Inference System (ANFIS) for modeling and predicting SR in end milling operation for spindle speed, feed rate and depth of cut. Two different membership functions (triangular and bell shaped) were used during hybrid-training process of ANFIS in order to compare the prediction accuracy of SR by the two membership functions.

Methodology

Proposed methodology, ANFIS, is based on hybridization of adaptive network and fuzzy logic. ANFIS⁷ allows to apply adaptive networks with learning and computing capabilities of fuzzy system. It uses a hybrid learning algorithm^{5,7} (combination of least squares method and back-propagation gradient descent method) to identify premise and consequent parameters of first order Takagi-Sugeno type fuzzy system for predicting SR in end milling.

Results and Discussion

Experimental data with regard to different cutting parameters and cutting performance are required to train the fuzzy inference system for modeling SR. A number of end milling experiment² was carried out using CNC vertical machining center. A high-speed steel (HSS) four-flute end-milling cutter (diam 19.05 mm) was used in this experiment to machine 6061 aluminum alloy. Spindle speed, feed rate and depth of cut were selected as the cutting parameters to analyze their effect on SR. The settings are: Spindle speed, 750, 1000, 1250 and 1500 rpm; Feed rate, 2.538, 3.807, 5.076, 6.345, 7.614, 8.883 and 10.152 mm/sec; and Depth of cut, 0.254, 0.762 and 1.27 mm. In all, 84 milling experiments were performed. CLA value for SR was measured by a stylus based profilometer.

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Table 1—Experimental data² for training data

Sl No.	Spindle speed, RPM	Feed rate, mm/sec	Depth of cut, mm	Surface roughness, μm
1	750	2.538	0.254	1.651
2	750	2.538	0.762	1.6002
3	750	2.538	1.27	1.8288
4	750	3.807	0.254	2.7686
5	750	3.807	0.762	2.5146
6	750	3.807	1.27	2.413
7	750	5.076	0.762	2.5908
8	750	5.076	1.27	2.3876
9	750	6.345	0.762	3.0988
10	750	6.345	1.27	2.6416
11	750	7.614	0.254	4.699
12	750	7.614	1.27	3.0734
13	750	8.883	0.762	4.1402
14	750	8.883	1.27	3.81
15	750	10.152	0.762	4.318
16	1000	2.538	0.254	1.4732
17	1000	2.538	0.762	1.9812
18	1000	2.538	1.27	1.5748
19	1000	3.807	1.27	2.5908
20	1000	5.076	0.254	3.302
21	1000	5.076	0.762	2.1336
22	1000	5.076	1.27	2.3368
23	1000	6.345	0.254	2.5654
24	1000	6.345	0.762	2.7432
25	1000	6.345	1.27	2.667
26	1000	7.614	0.254	3.5052
27	1000	8.883	0.254	3.7846
28	1000	8.883	0.762	3.683
29	1000	10.152	0.254	4.1402
30	1000	10.152	0.762	3.8862
31	1250	2.538	0.254	1.27
32	1250	2.538	0.762	1.6002
33	1250	2.538	1.27	1.8034
34	1250	3.807	0.254	2.0066
35	1250	3.807	0.762	2.0574
36	1250	3.807	1.27	2.3368
37	1250	5.076	0.254	2.5654
38	1250	5.076	1.27	2.159
39	1250	6.345	0.762	2.4384
40	1250	7.614	0.254	2.921
41	1250	7.614	0.762	2.3368
42	1250	7.614	1.27	2.413
43	1250	8.883	0.254	3.175
44	1250	8.883	0.762	2.54
45	1250	8.883	1.27	2.667
46	1250	10.152	0.254	3.937
47	1250	10.152	0.762	2.7686
48	1500	2.538	0.254	0.9398
49	1500	3.807	0.254	1.3208
50	1500	3.807	0.762	1.8542
51	1500	5.076	0.254	2.2352
52	1500	6.345	0.254	2.6924
53	1500	6.345	1.27	2.5146
54	1500	7.614	0.254	3.0226
55	1500	7.614	1.27	2.6416
56	1500	8.883	0.254	2.9972
57	1500	8.883	1.27	2.8702
58	1500	10.152	0.254	3.0226
59	1500	10.152	0.762	2.6162
60	1500	10.152	1.27	2.7686

Table 2—Premise parameters of fuzzy system for triangular MF

Spindle speed			
	a_i	b_i	c_i
SS	375.00	750.01	1125.02
MS	749.99	1124.95	1500.06
HS	1124.89	1499.94	1874.99
Feed rate			
VLF	0.0063	3.0295	5.0731
LF	2.1588	5.4064	7.9694
MMF	5.0756	8.2947	10.1516
HF	8.8833	10.6764	12.69
Depth of cut			
SA	-0.2540	0.2540	0.7618
MD	0.2544	0.7620	1.2699
DE	0.7621	1.27	1.778

Table 3—Premise parameters of fuzzy system for bell-shaped MF

Spindle speed			
	a_i	b_i	c_i
SS	187.488	2.4079	749.992
MS	187.496	-0.8806	1125.01
HS	187.569	1.2233	1499.94
Feed rate			
VLF	1.3431	2.1314	2.7963
LF	1.3093	1.8026	5.7734
MMF	1.6095	2.1117	7.6402
HF	0.6489	2.1404	10.5234
Depth of cut			
SA	0.2176	2.0032	0.2369
MD	0.1924	2.0056	0.7725
DE	0.2524	2.0007	1.2693

A total of 60 sets of data were selected from the total of 84 sets obtained in the end milling experiments² for training in ANFIS (Table 1). This training adjusts the membership function parameters. In some cases, data was collected using noisy measurements, and the training data cannot be representative of all the features of the data that will be presented to the model. So, model validation is needed to cross validate the fuzzy inference system using testing data set, which is useful in checking the generalization capability of the resulting fuzzy inference system. That is why, other 24 sets were then used for testing after the training was completed to verify the accuracy of the predicted values of SR.³

Spindle speed, feed rate and depth of cut are the inputs and SR is the output of the system. Triangular shape (TS) and bell shape (BS) are used for the

Table 4—Consequent parameter of the fuzzy system for triangular MF

Rule No.	p_i	q_i	r_i	t_i
1	0.00219	-0.93332	0.28075	1.10532
2	0.00166	0.93044	-0.99785	-1.30952
3	-0.00358	0.87497	1.16618	0.91825
4	0.01748	-2.61258	0.91671	3.60911
5	-0.00147	0.23267	1.20618	1.58291
6	-0.00265	0.54293	0.78275	0.61634
7	0.01288	-1.18882	1.29794	5.11002
8	0.00337	0.26394	-0.34901	-0.45802
9	-0.00670	0.71592	1.21184	0.95421
10	0.00426	0.15145	0.00379	0.01492
11	0.00729	-0.11193	-0.00840	-0.01102
12	0.00500	0.05943	0.00743	0.00585
13	0.00191	0.05265	-0.33689	-1.32632
14	-0.00162	0.53554	1.19737	1.57136
15	0.00054	1.83909	-1.39937	-1.10186
16	0.00836	-0.58826	-1.10001	-4.33073
17	0.00234	0.54933	-1.44736	-1.89942
18	-0.00245	1.39701	-0.93927	-0.73958
19	0.00689	0.15346	-1.55746	-6.13175
20	-0.00170	0.43031	0.41879	0.54960
21	-0.00157	0.86344	-1.45417	-1.14501
22	0.00517	-0.18162	-0.00454	-0.01789
23	0.00137	0.13444	0.01009	0.01324
24	0.00334	-0.07121	-0.00891	-0.00701
25	0.00020	0.02367	0.11240	0.44252
26	0.00092	0.33251	-0.39949	-0.52427
27	0.00027	-0.02041	0.46689	0.36763
28	-0.00032	0.22579	0.36701	1.44492
29	0.00015	0.17017	0.48290	0.63373
30	0.00098	0.05712	0.31338	0.24676
31	0.00091	-0.06359	0.51964	2.04582
32	6.07883	0.32224	-0.13973	-0.18337
33	0.00049	0.12549	0.48517	0.38203
34	0.00160	0.06062	0.00152	0.00597
35	0.00205	-0.04484	-0.00336	-0.00442
36	0.00168	0.02378	0.00297	0.00234

membership function distribution for the input variables. First-order Sugeno fuzzy inference system is used in this work. The fuzzy expressions for spindle speed are: SS, Slow Speed; MS, Medium Speed; and HS, High Speed. Fuzzy expressions for feed rate are: VLF, Very Low Feed; LF, Low Feed; MMF, Medium Feed; and HF, High Feed. Fuzzy expressions for depth of cut are: SA, Shallow; MD, Medium Deep; and DE, Deep. Number of fuzzy rules in a fuzzy system is related to the number of fuzzy sets for each input variable. The inputs, spindle speed, feed rate and depth of cut, are classified into 3, 4 and 3 fuzzy sets respectively. Feed rate is classified into more number of fuzzy sets because it has most impact on SR. Therefore, maximum number of rules for this system can be 36. Thus, a typical rule will look as: If cutting speed (v_i) is MS and feed rate (f_i) is MMF and depth of cut (d_i) is DE, then

$$SR = p_i v_i + q_i f_i + r_i d_i + c_i$$

where p_i , q_i , r_i , c_i are the design parameters referred as 'consequent parameters'.

During training in ANFIS, 60 sets of experimental data were used to conduct 500 cycles of learning. ANFIS learning scenario for predicting SR is as follows: number of nodes = 98, number of linear parameters = 144, number of non-linear parameters =

30, total number of parameters = 174, number of fuzzy rules = 36.

The values of premise parameters of TS membership function (Table 2) and BS membership function (Table 3) for fuzzy sets were obtained after training for modelling SR. The consequent parameters were obtained after training using TS (Table 4) and BS (Table 5) membership function. Predicted values and experimental data² of SR after training were

Table 5—Consequent parameter of the fuzzy system for Bell-shaped MF

Rule No.	p_i	q_i	r_i	t_i	Rule No.	p_i	q_i	r_i	t_i
1	-0.00344	-0.09154	0.68506	2.73667	19	-0.03540	1.94174	3.70528	14.56282
2	-0.00283	1.74311	-0.65356	-0.84977	20	-0.00883	1.14538	0.26472	0.50020
3	-0.00151	-2.37192	2.24385	1.75352	21	-0.03112	3.41585	2.28287	1.84624
4	0.02314	-4.08875	2.76442	10.63066	22	-0.00271	0.92705	-0.08574	-0.33677
5	-0.00498	-1.19696	3.32778	4.47678	23	0.00002	0.24857	-0.01213	-0.02008
6	0.01698	-4.85373	1.89127	1.61931	24	-0.00147	0.32191	0.00197	0.00021
7	0.02947	-3.66165	3.54651	13.93878	25	-0.00159	0.13495	0.61085	2.44021
8	0.00883	-0.34787	0.25339	0.47879	26	-0.00293	0.92016	-0.58275	-0.75771
9	0.00621	-1.28623	2.18510	1.76717	27	0.00483	-3.19819	2.00077	1.56356
10	-0.00946	1.09781	-0.08206	-0.32235	28	-0.00422	1.61797	2.46494	9.47899
11	0.00294	0.34390	-0.01161	-0.01921	29	0.00526	-1.76129	2.96729	3.99181
12	-0.00172	0.71144	0.00189	0.00020	30	0.02593	-5.83458	1.68632	1.44384
13	-0.00210	0.50285	0.71574	2.85921	31	0.01473	-1.59845	3.16229	12.42871
14	0.00657	-0.33885	-0.68281	-0.88781	32	0.00573	-0.32069	0.22593	0.42690
15	-0.01162	4.58141	2.34430	1.83202	33	0.02068	-2.36732	1.94835	1.57570
16	-0.00916	-1.70646	2.88819	11.10663	34	-0.00435	0.82461	-0.07317	-0.28741
17	-0.01464	2.52974	3.47678	4.67721	35	-0.00047	0.32332	-0.01035	-0.01714
18	-0.03630	7.71059	1.97585	1.69173	36	-0.00209	0.70404	0.00169	0.00018

Table 6—Comparison of surface roughness predicted from ANFIS and experimental values for some of the training cases²

Spindle speed RPM	Feed rate mm/sec	Depth of cut mm	Surface roughness μm Experimental result	ANFIS predicted value			
				Triangular MF		Bell-shaped MF	
				Surface roughness μm	Abs. % Error	Surface roughness μm	Abs. % Error
750	2.538	0.762	1.6002	1.59	0.6374	1.6	0.0125
750	3.807	0.254	2.7686	2.75	0.6718	2.74	1.0330
750	3.807	1.27	2.413	2.43	0.7045	2.41	0.1243
750	6.345	1.27	2.6416	2.66	0.6965	2.64	0.0606
750	7.614	1.27	3.0734	3.04	1.0867	3.06	0.4360
750	8.883	1.27	3.81	3.83	0.5249	3.82	0.2625
1000	2.538	0.762	1.9812	2.00	0.9489	1.97	0.5653
1000	5.076	0.762	2.1336	2.16	1.2373	2.14	0.2999
1000	6.345	0.762	2.7432	2.71	1.2103	2.73	0.4812
1000	7.614	0.254	3.5052	3.50	0.1484	3.49	0.4336
1000	10.152	0.254	4.1402	4.14	0.0048	4.14	0.0048
1250	2.538	0.762	1.6002	1.58	1.2623	1.61	0.6124
1250	3.807	0.762	2.0574	2.09	1.5845	2.04	0.8457
1250	5.076	1.27	2.159	2.12	1.8064	2.16	0.0463
1250	7.614	0.762	2.3368	2.29	2.0027	2.33	0.2910
1250	8.883	0.762	2.540	2.57	1.1811	2.57	1.1811
1500	3.807	0.762	1.8542	1.84	0.7658	1.87	0.8521
1500	7.614	0.254	3.0226	3.02	0.0860	3.01	0.4169
1500	8.883	0.254	2.9972	2.98	0.5739	3.01	0.4271
1500	10.152	1.27	2.7686	2.77	0.0506	2.77	0.0506

Table 7—Comparison of surface roughness predicted from ANFIS and experimental values for the test cases²

Spindle speed RPM	Feed rate mm/sec	Depth of cut mm	Surface roughness μm Experimental result	ANFIS predicted value			
				Triangular MF		Bell-shaped MF	
				Surface roughness μm	Abs. %Error	Surface roughness μm	Abs. %Error
750	5.076	0.254	3.6576	3.69	0.8858	3.66	0.0656
750	6.345	0.254	3.175	3.13	1.4173	3.17	0.1575
750	7.614	0.762	3.7338	3.72	0.3696	3.72	0.3696
750	8.883	0.254	4.5212	4.54	0.4158	4.52	0.0265
750	10.15	0.254	4.7498	4.75	0.0042	4.75	0.0042
750	10.15	1.270	4.3688	4.37	0.0275	4.37	0.0275
1000	3.807	0.254	2.3368	2.38	1.8487	2.39	2.2766
1000	3.807	0.762	2.3876	2.36	1.1559	2.40	0.5194
1000	7.614	0.762	3.1496	3.20	1.6002	3.17	0.6477
1000	7.614	1.270	2.1844	2.27	3.9187	2.20	0.7142
1000	8.883	1.270	2.8448	2.79	1.9263	2.83	0.5202
1000	10.15	1.270	3.6068	3.61	0.0887	3.61	0.0887
1250	5.076	0.762	2.5146	2.49	0.9783	2.51	0.1829
1250	6.345	0.254	2.6924	2.55	5.2889	2.68	0.4606
1250	6.345	1.270	2.4384	2.49	2.1162	2.44	0.0656
1250	10.15	1.270	3.0734	3.07	0.1106	3.07	0.1106
1500	2.538	0.762	1.4224	1.43	0.5343	1.41	0.8718
1500	2.538	1.270	1.4224	1.43	0.5343	1.42	0.1687
1500	3.807	1.270	1.778	1.76	1.0124	1.78	0.1125
1500	5.076	0.762	2.0828	2.09	0.3457	2.09	0.3457
1500	5.076	1.270	2.3876	2.40	0.5194	2.39	0.1005
1500	6.345	0.762	2.1082	2.10	0.3889	2.09	0.8633
1500	7.614	0.762	2.2098	2.23	0.9141	2.24	1.3667
1500	8.883	0.762	2.5908	2.58	0.4169	2.57	0.8028

compared by ANFIS (Table 6) with TS and BS membership functions for some of the training cases. Simulation result shows that average error (0.87%) of the modelling of SR when TS membership function is used, and average error (0.43%) when BS membership function is used in ANFIS, is lesser than that from multiple regression method². Comparison (Table 7) made between predicted value using TS membership function and BS membership function with some of the testing data shows that the average error of the prediction of SR is 1.117 percent (accuracy, 98.883%) when TS membership function is used in ANFIS. When BS membership function is adopted, average error is 0.453 percent (accuracy, 99.547%). In both cases, prediction error is smaller than that from multiple regression method² (average error, 9.97%). The comparison indicates that the adoption of both membership functions in ANFIS achieved better accuracy than multiple regression model². The BS membership function in ANFIS achieves slightly higher prediction accuracy than TS membership function. This is because SR exhibits non-linearity with respect to cutting parameters.

Conclusions

An ANFIS based on first-order Sugeno fuzzy inference system is used to predict surface roughness in end milling operation. Using combination of back-propagation gradient descent method and least squares method, ANFIS can automatically and effectively generate optimal triangular and bell-shaped membership functions and corresponding rule base, which exempt the design of fuzzy inference system from heavy reliance on human experts. The output of proposed systems has been compared with experimental results and the multiple regression analysis. Comparison shows that the proposed method outperforms the existing multiple regression method in terms of modelling accuracy.

Acknowledgements

Author thanks Director, CMERI, Durgapur, for permission to publish this paper, and acknowledges support from Machine Design & Development Group, CMERI.

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