A CONTRIBUTION TO THE IDENTIFICATION IN FUZZY-LOGIC CONTROL

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Received January 23, 1989
Accepted September 22, 1989

A linguistic identification of a system controlled by a fuzzy-logic controller is presented. The information about the behaviour of the system, concentrated in time-series, is analysed from the point of its description by linguistic variable and fuzzy subset as its quantifier. The partial input/output relation and its strength is expressed by a sort of correlation tables and coefficients. The principles of automatic generation of model statements are presented as well.

When trying to construct a linguistic model for a fuzzy-logic controller (FLC) we are deeply interested in the basic parameters of the controlled system description: the order of its model and all partial input/output time delays. The system under control must be properly identified with the aid of methods and tools which are immanent to the linguistic approach used. In contrast with the conventional approach on differential or difference equations our effort is concentrated on a proper time-relational context of the statement "if A then B" as accepted for this type of model form.

The natural base for model building is a sufficiently exhaustive time series of experimental or process data concerning all the variables influencing significantly the behaviour of the system. The series is not only a sequence of time-ordered n-tuples of data, it represents also the whole history of time-relational cause between perturbations and corresponding responses. It is the aim of this paper to bring a contribution to the metodology of time-series analysis from the point of its description by linguistic variable. We speak about "linguistic identification" for short.

The problem of this sort of identification was for the first time discussed by Tong[1]. The input/output data, quantised according to individual term-sets of accepted linguistic evaluating scales, were confronted in their frequency of occurrence through so-called "correlation tables" to estimate the very likely time delay for input variables. Such an approach may help significantly also for the construction of the linguistic model itself and check the efficiency of the subtlety of discretisation of variables's universe and evaluating scale.

Linguistic Correlation Between FLC *Variables*

Because of linguistic form of FLC, all data of experimental or process time-series must be first converted into the accepted term-sets of evaluating scales. It is possible then to investigate the pair input/output coincidence of the variables of the system under control and their frequency within the series. The resulting tables will be called "linguistic correlations tables".

These correlation tables may suffer either from time and effort consumption (especially in problems with several variables) and/or from their rather difficult quantitative evaluation. To avoid this, an automatic identification algorithm including the mentioned pair correlation, as an analogy to the conventional non-parametric correlation analysis, is proposed. The algorithm forms an independent computational block enabling the automatic quantisation of data, its ordering into correlation tables with necessary evaluation of corresponding correlation coefficients and their orientation, as the most decisive points for the identification of the system.

The simplest situation is with equal number of evaluating terms for all variables of the FLC. The content of the square correlation table ($m = n$) is then evaluated through a sort of correlation coefficient

$$r'_1 = \sum_{i=1}^{m} \sum_{j=1}^{n} p(i,j) \, . \, |j - q_1(i)|/(N(n-1)) \, ; \quad q_1(i) = i \tag{1}$$

for a direct relation and

$$r'_2 = \sum_{i=1}^{n} \sum_{j=1}^{m} p(i,j) \, . \, |i - q_2(j)|/(N(n-1)) \, ; \quad q_2(j) = n - j + 1 \tag{2}$$

for a reverse relation between $x^k(t - \tau)$ as the k-th input variable and $y(t)$ as the output one. i, j are the indices in the corresponding universa U^k, V, $p(i,j)$ is the frequency of the ordered pair $(x^k_i(t - \tau), y(t))$ in the time-series, m, n are the numbers of elements in the corresponding evaluating scales (> 1 and the same for x^k and y), N is the total number of non-zero elements in the correlation table (number of data) and τ is the time shifting between variables of the pair (x^k, y). Apparently, the coefficients r'_1 and r'_2 are non-negative quantities from $\langle 0; 1 \rangle$, the closer to zero are their values the more evident are the pressumed relations.

Another situation is with non-equal number of evaluating terms that conveys to a non-square correlation table. Such a case is complicated from the point of the row/column comparison, i.e. from the point of the philosophy of the analysis. As a way out, a quasi-square correlation table is proposed through the successive association of abundant rows or columns by an analogy of the method of "moving average" known from statistics. This heuristic approach uses for the general case $n > m$ the quantities $q_1(i)$ and $q_2(j)$ in the forms

$$q_1(i) = i + (n - m)/2 \tag{3}$$

and

$$q_2(j) = (m + n)/2 - j + 1\,. \tag{4}$$

The comparison of the coefficients r'_1 and r'_2 brings the elementary information on the most probable time shifting between x^k and y on the one hand and the orientation of the relation between them on the other. Such information serves as a starting point for further analysis of relations among variables of the model.

The coefficients in Eqs (*1*) and (*2*) suffer, however, from the lack of one important feature of model-making and that from the impossibility of implicit evaluation of the extend of the data set. The simplest way to remove this inconvenience is to extend both the forms (*1*) and (*2*) by the term $(N/(N - 1))^K$ so that

$$r_1 = r'_1(N/(N - 1))^K \tag{5}$$

and

$$r_2 = r'_2(N/(N - 1))^K\,. \tag{6}$$

The meaning of this adaptation consists in the sharp discrimination of the sets with smaller number of elements. The discrimination is further emphasized by a user's view on the value of the non-negative exponent K. Apparently, the role of this adaptation is diminished for sufficiently large sets $(\lim (N/(N - 1) | N \to \infty) = 1)$. The vanishing normality of Eqs (*1*) and (*2*) is irrelevant here, because the strongest relation within the correlated set is indicated by the value of r_1 or r_2 close to zero. In case of comparison of different models for the same data set, the extension with the forms (*5*) and (*6*) may be omitted.

The quantisation of particular data with respect to the corresponding universa is made according to the linear interpolation formula

$$j = \mathrm{INT}\left[1{\cdot}5 + \frac{t - x_i^1}{x_i^{Ni} - x_i^1}(Ni - 1)\right], \tag{7}$$

where j is current index of an element of the universe of i-th variable $(x_i^j \in X_i)$, Ni the number of elements of the discrete net of X_i, t a real value of the element of the data set, INT [$*$] the integer part of $*$. The reverse form of Eq. (*7*) is

$$x_i^j = x_i^1 + \frac{j - 1}{Ni - 1}(x_i^{Ni} - x_i^1)\,. \tag{8}$$

Designating an evaluating fuzzy subset (term) for X_i as $A_{ik} \subset X_i$ with its numerical representative $a_{ik} \in X_i$ (Ki being the number of all evaluating fuzzy subsets for the variable X_i), the confrontation of the data set with the corresponding fuzzy-linguistic evaluating scale is performed according to the scheme

$$|x_i^j - a_{is}| = \underset{k}{\text{MIN}} |x_i^j - a_{ik}| \; ; \quad k = 1, \ldots, Ki \tag{9}$$

(a_{is} is the quantised form (*8*) of a general value t). The notion "numerical representative of A_{ik}" is quite general, it may correspond with the peak of the membership function of A_{ik} or the center of the area under it, etc. For the purpose of the mentioned confrontation, the quantisation procedure (*7*) may be avoided and the value t can be used in Eq. (*9*) instead of x_i^j.

Example 1. pH is measured and controlled by a FLC in a flow system sulphuric acid/natrium hydroxid (with water as inert), equipped with a digital pH-meter, acid and alkali peristaltic pumps and a mixer. All these items are interconnected with the TNS microcomputer (64 kBytes). We suppose that the system can be described by a dynamic model in the linguistic form

$$Y(t) = f(X(t - 1), U_1(t - \tau_1), U_2(t - \tau_2)) , \tag{10}$$

where the error Y (as the difference between the measured pH and a set-point) depends on the current pH level X and the activity of the acid (U_1) and alkali (U_2) pumps. X and Y are measured in pH units, U_1, U_2 are measured in 0·05 mV. The universe of Y is given by the interval $\langle -1{\cdot}0; 1{\cdot}0 \rangle$ with 9 elements and 9 evaluating terms, the universe of X represents the interval $\langle 2; 8 \rangle$ with 7 elements and 3 terms. The universa of both U's are determined by the interval $\langle 0; 250 \rangle$ with 11 elements and 11 evaluating terms. A part of the pH-control time-series with numerical and term representation is given in Table I. We are interested in the values of the time-delay parameters τ_1, τ_2, best identifying the model (*10*).

As seen from Table I, there may be expected the possibility of non-linearity in the relation of Y with both U_1 and U_2. The time-series is therefore analysed from the point of three pH levels evaluated by the mentioned three linguistic terms. The time dependence in the control history is considered to be not more then four sampling intervals. The results of the linguistic correlation analysis are summarized in Table II. According to the minimum values of r_1 or r_2, the static gain orientation sign (U_1/Y) is positive and sign (U_2/Y) is negative. The parameter τ_1 is 1 for all investigated pH levels, τ_2 equals 1 for the pH levels 1, 3 and equals 2 for the level 2. The orientation of U_i/Y is quite comprehensible when taking into account the definition of the error Y. The activity of acid pump (i.e. U_1) is conditioned by positive values of Y (the neutralized medium is basic) whilst the activity of alkalli pump (U_2) corresponds with negative Y's (the neutralized medium is acidic). The fact of $\tau_2 = 2$ for the

TABLE I

The primary and quantised data of pH-control time series. Discrete step — 10 s sampling interval

Step	Error Y		pH-measured X		Acid pump U_1		Alkali pump U_2	
	value	term	value	term	value	term	value	term
1	−0·89	1	2·11	1	0	1	199	9
2	−0·85	2	2·15	1	0	1	186	8
3	−0·73	2	2·27	1	0	1	146	7
4	−0·54	3	2·46	1	0	1	89	5
5	−0·15	4	2·85	1	30	2	0	1
6	0·02	5	4·02	2	0	1	23	2
7	0·45	7	4·45	2	54	3	0	1
8	0·34	6	4·34	2	36	2	0	1
9	0·22	6	4·22	2	23	2	0	1
10	0·59	7	5·59	2	150	7	0	1
11	0·20	6	5·20	2	29	2	0	1
12	0·00	5	5·00	2	0	1	0	1
13	0·23	6	5·23	2	35	2	0	1
14	−0·30	4	5·70	2	0	1	103	5
15	0·02	5	6·02	3	47	3	0	1
16	0·21	6	6·21	3	50	3	0	1
17	0·33	6	6·33	3	75	4	0	1
18	−0·28	4	6·72	3	0	1	144	7
19	−0·01	5	6·99	3	0	1	0	1
20	0·11	5	7·11	3	62	3	0	1
21	0·19	6	7·19	3	77	4	0	1
22	−0·58	3	7·42	3	0	1	227	10
23	−0·41	3	7·59	3	0	1	220	10
24	−0·30	4	7·70	3	0	1	213	9
25	−0·23	4	7·77	3	0	1	207	9
26	−0·07	5	7·93	3	0	1	184	8
27	−0·03	5	7·97	3	0	1	170	8
28	0·01	5	8·01	3	92	5	0	1
29	0·05	5	8·05	3	110	5	0	1
30	1·13	9	6·13	3	200	9	0	1
31	0·98	9	5·98	2	146	7	0	1
32	0·51	7	5·51	2	76	4	0	1
33	0·27	6	5·27	2	41	3	0	1
34	0·20	6	5·20	2	29	2	0	1
35	1·00	9	5·00	2	150	7	0	1
36	0·57	7	4·57	2	72	4	0	1
37	0·34	6	4·34	2	36	2	0	1
38	0·10	5	4·10	2	23	2	0	1
39	−0·13	4	3·87	1	0	1	48	3
40	−0·17	4	3·83	1	0	1	97	5

TABLE I
(*Continued*)

Step	Error Y value	Error Y term	pH-measured X value	pH-measured X term	Acid pump U_1 value	Acid pump U_1 term	Alkali pump U_2 value	Alkali pump U_2 term
41	0·75	8	3·75	1	95	5	0	1
42	0·67	8	3·67	1	40	3	0	1
43	0·55	7	3·55	1	30	2	0	1
44	0·52	7	3·52	1	26	2	0	1
45	0·20	6	3·20	1	20	2	0	1

second pH level is supported by the shape of the titration curve, witnessing about this level (pH 4 ÷ 6) as the most sensitive one (the first inflexion point of the system sulphuric acid/natrium hydroxid is approximately at pH 5 and the curve is steep enough here to be characterized as jump-sensitive). It is, therefore, preferrable to face the expected pH change within this area a longer period before. With the above-mentioned universa and linguistic evaluating scales the information on the static gain orientation and time delay parameters for individual variables forms the base

TABLE II
The partial correlation coefficients r_1, r_2 for the relations (Y, U_1) and (Y, U_2)

Time delay τ	pH-level term X	U_1 r_1	U_1 r_2	U_2 r_1	U_2 r_2
1		0·2182	0·5273	0·4909	0·2909
2	1	0·25	0·49	0·46	0·36
3		0·2778	0·4778	0·3778	0·4222
4		0·2875	0·4375	0·3375	0·4375
1		0·25	0·3125	0·45	0·3625
2	2	0·3125	0·3125	0·45	0·3375
3		0·325	0·275	0·4375	0·3625
4		0·2812	0·3062	0·475	0·3875
1		0·1733	0·44	0·4933	0·3333
2	3	0·1933	0·42	0·42	0·4067
3		0·2	0·42	0·44	0·3867
4		0·24	0·4133	0·4133	0·3933

for further construction of the linguistic model describing the dynamics of the controlled system. Of course, the time-series used in this example is only of illustrative meaning and does not pretend to be quite descriptive and exhaustive. On the other hand, the results obtained correspond perfectly with the qualitative nature of the given pH-control system and may be fully supported by a long-period experimental experience with FLC and conventional controllers.

Automatic Construction of the Linguistic Model of FLC

The automatic construction of a conditional statement of the linguistic model for FLC is conditioned by the knowledge of these data:
- real set-point value SP(K) (K – sampling interval index);
- term-quantised set-point value PT(K);
- real state-of-the-system value X(K);
- term-quantised state-of-the-system value SV(K);
- real control value U(J, K) (J – control variable index);
- term-quantised control value CV(J, K);
- estimated static gain value U(J, K)/SP(K) = SU(J, K);
- term-quantised static gain value SG(J, K);
- time-delay parameter value for state (TS) and control (TC(J)) variable.

All term-quantised values are obtained according to the scheme (*9*). Quite generally, the parallel for the model (*10*) may be expressed by the matrix of conditional statements MS(I, L) (I index of variable, L index of statement), e.g., in the form

$$\begin{aligned}
&\text{“IF” part:} && \mathrm{MS}(1, L) = \mathrm{PT}(K)\\
& && \mathrm{MS}(2, L) = \mathrm{SV}(K\text{-TS})\\
&\text{“THEN” part:} && \mathrm{MS}(I, L) = \mathrm{CV}(I, K\text{-TC}(I))\,; \quad I = J + 2;\ J = 1, \ldots, NC\,,
\end{aligned}$$

where NC is the number of control variables. Apparently, such a form may be fully submitted to the structure of a difference equation in its Z-transform $X(z)\,A(z^{-1}) = U(z)\,B(z^{-1})$ describing the dynamics of the system under control.

Any created statement of the model is checked before its applying to the given situation by the couple of logical premises

$$\begin{gathered}
[\mathrm{X}(K) \geqq \mathrm{SP}(K)] \text{ and } [\mathrm{sign}\,(\mathrm{SU}(J, K)) * \mathrm{MS}(J, L) \geqq \mathrm{sign}\,(\mathrm{SU}(J, K)) * \mathrm{SG}(J, K)]\\
[\mathrm{X}(K) \leqq \mathrm{SP}(K)] \text{ and } [\mathrm{sign}\,(\mathrm{SU}(J, K)) * \mathrm{MS}(J, L) \leqq \mathrm{sign}\,(\mathrm{SU}(J, K)) * \mathrm{SG}(J, K)]
\end{gathered} \tag{11}$$

J being the index from "THEN" part of the statement matrix. In case the couple of premises (*11*) is of FALSE value, the corresponding matrix element MS(J, L) is corrected as

$$[\mathrm{MS}(J, L)]_{\mathrm{corr}} = 2 * \mathrm{SG}(J, K) - \mathrm{MS}(J, L)\,. \tag{12}$$

TABLE III
The OSA prediction for the pH-control (time series from Table I)

Step	Y(exp)		Y(OSA)		Statement	
	value	term	value	term	No.	form
1	−0·89	1	−1·00	1	1	1 1 1 9
2	−0·85	2	−0·75	2	2	2 1 1 8
3	−0·73	2	−0·75	2	2	2 1 1 8
4	−0·54	3	−0·50	3	4	3 1 1 5
5	−0·15	4	−0·25	4	5	4 1 2 1
6	0·02	5	0·00	5	6	5 2 1 1
7	0·45	7	0·50	7	7	7 2 3 1
8	0·34	6	0·25	6	8	6 2 2 1
9	0·22	6	0·25	6	8	6 2 2 1
10	0·59	7	0·50	7	7	7 2 3 1
11	0·20	6	0·25	6	8	6 2 2 1
12	0·00	5	0·00	5	6	5 2 1 1
13	0·23	6	0·25	6	8	6 2 2 1
14	−0·30	4	−0·25	4	10	4 2 1 1
15	0·02	5	0·00	5	11	5 3 1 1
16	0·21	6	0·25	6	12	6 3 4 1
17	0·33	6	0·25	6	12	6 3 4 1
18	−0·28	4	−0·25	4	14	4 3 1 9
19	−0·01	5	0·00	5	11	5 3 1 1
20	0·11	5	0·00	5	11	5 3 1 1
21	0·19	6	0·25	6	12	6 3 4 1
22	−0·58	3	−0·50	3	3	3 3 1 10
23	−0·41	3	−0·50	3	3	3 3 1 10
24	−0·30	4	−0·25	4	14	4 3 1 9
25	−0·23	4	−0·25	4	14	4 3 1 9
26	−0·07	5	0·00	5	11	5 3 1 1
27	−0·03	5	0·00	5	11	5 3 1 1
28	0·01	5	0·00	5	11	5 3 1 1
29	0·05	5	0·00	5	11	5 3 1 1
30	1·13	9	1·00	9	13	9 3 9 1
31	0·98	9	1·00	9	9	9 2 7 1
32	0·51	7	0·50	7	7	7 2 3 1
33	0·27	6	0·25	6	8	6 2 2 1
34	0·20	6	0·25	6	8	6 2 2 1
35	1·00	9	1·00	9	9	9 2 7 1
36	0·57	7	0·50	7	7	7 2 3 1
37	0·34	6	0·25	6	8	6 2 2 1
38	0·10	5	0·00	5	6	5 2 1 1
39	−0·13	4	−0·25	4	5	4 1 2 1
40	−0·17	4	−0·25	4	5	4 1 2 1

TABLE III
(*Continued*)

Step	Y(exp)		Y(OSA)		Statement	
	value	term	value	term	No.	form
41	0·75	8	0·75	8	15	8 1 5 1
42	0·67	8	0·75	8	15	8 1 5 1
43	0·55	7	0·50	7	16	7 1 2 1
44	0·52	7	0·50	7	16	6 1 2 1
45	0·20	6	0·25	6	17	6 1 2 1

The number of evaluating terms for the J-th variable is NT(J). The corrected statement is applied to the control and simultaneously included into the model. The starting value of MS(J, L) is generally conditioned by the values from "IF" part of MS according to a particular prescription or, more simply, to the recent history of the control. But, almost as a rule, the partial form (*11*) with the mirror-like correction (*12*), i.e. the key role of the partial static gain orientation, has been quite decisive in majority of problems solved.

To illustrate the efficiency of the presented procedure, the OSA (one-step-ahead) prediction with successively constructed fuzzy-linguistic model of the controller can be used. Of course, the measure of the model performance accuracy has to be evaluated from the point of the density of the discrete net of the universa and evaluating scales.

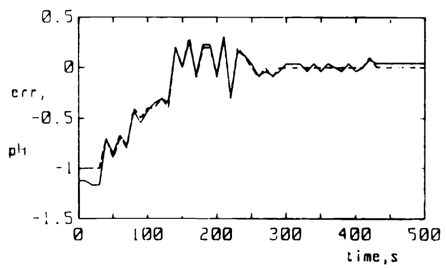

FIG. 1
Experimental data and OSA prediction: ——— experimental data, — — — OSA prediction

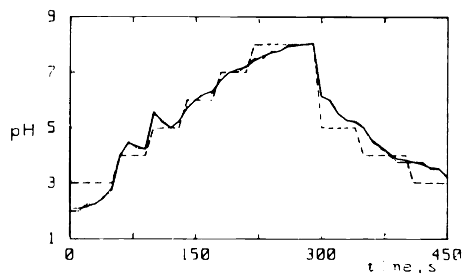

FIG. 2
Experimental data and OSA prediction: ——— experimental data, — — — set-points, –·–·–· OSA prediction

TABLE IV

The pH-control and OSA predictions for the increased number of universa and evaluating scales elements (uniform 21)

Step	Error				pH-measured		Acid pump		Alkali pump		Statement
	Y(exp)		Y(OSA)		X		U_1		U_2		
	value	term	value	term	value	term	value	term	value	term	
1	−1·13	1	−1·00	1	3·87	7	0	1	250	21	1 7 1 21
2	−1·17	1	−1·00	1	3·83	7	0	1	250	21	1 7 1 21
3	−1·17	1	−1·00	1	3·87	7	0	1	250	21	1 7 1 21
4	−0·70	4	−0·70	4	4·30	9	0	1	158	14	4 9 1 21
5	−0·86	2	−0·90	2	4·14	8	0	1	193	16	2 8 1 14
6	−0·66	4	−0·70	4	4·34	9	0	1	149	13	4 9 1 21
7	−0·78	3	−0·80	3	4·22	8	0	1	176	15	3 8 1 13
8	−0·43	7	−0·40	7	4·57	10	0	1	97	9	7 10 1 15
9	−0·55	6	−0·50	6	4·45	9	0	1	123	11	6 9 1 9
10	−0·43	7	−0·40	7	4·57	10	0	1	97	9	7 10 1 15
11	−0·35	7	−0·40	7	4·65	10	0	1	79	7	7 10 1 15
12	−0·31	8	−0·30	8	4·69	10	0	1	70	7	8 10 1 7
13	−0·35	7	−0·40	7	4·65	10	0	1	45	5	7 10 1 15
14	0·20	13	0·20	13	5·20	12	0	1	29	3	13 12 5 1
15	0·00	11	0·00	11	5·00	11	0	1	23	3	11 11 3 1
16	0·27	14	0·30	14	5·27	12	106	9	0	1	14 12 9 1
17	−0·08	10	−0·10	10	4·92	11	30	3	0	1	10 11 3 1
18	0·23	13	0·20	13	5·23	12	0	1	91	8	13 12 5 1
19	0·23	13	0·20	13	5·23	12	35	4	0	1	13 12 5 1
20	−0·08	10	−0·10	10	4·92	11	30	3	0	1	10 11 3 1
21	0·31	14	0·30	14	5·31	12	47	5	0	1	14 12 9 1

22	0·31	8	−0·30	8	4·69	10	0	1	70	7	8	10	1	7
23	0·16	13	0·20	13	5·16	12	0	1	29	3	13	12	5	1
24	0·12	12	0·10	12	5·12	11	0	1	23	3	12	11	3	1
25	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1
26	−0·08	10	−0·10	10	4·92	11	0	1	45	5	10	11	3	1
27	−0·04	11	0·00	11	4·96	11	0	1	45	5	11	11	3	1
28	−0·08	10	−0·10	10	4·92	11	0	1	45	5	10	11	3	1
29	−0·04	11	0·00	11	4·96	11	0	1	45	5	11	11	3	1
30	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1
31	0·04	11	0·00	11	5·04	11	0	1	23	3	11	11	3	1
32	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1
33	−0·04	11	0·00	11	4·96	11	30	3	0	1	11	11	3	1
34	0·04	11	0·00	11	5·04	11	0	1	23	3	11	11	3	1
35	−0·04	11	0·00	11	4·96	11	0	1	45	5	11	11	3	1
36	0·04	11	0·00	11	5·04	11	0	1	23	3	11	11	3	1
37	0·00	11	0·00	11	5·00	11	30	3	0	1	11	11	3	1
38	−0·04	11	0·00	11	4·96	11	0	1	45	5	11	11	3	1
39	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1
40	−0·04	11	0·00	11	4·96	11	0	1	45	5	11	11	3	1
41	0·00	11	0·00	11	5·00	11	23	3	0	1	11	11	3	1
42	0·08	12	0·10	12	5·08	11	0	1	23	3	12	11	3	1
43	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1
44	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1
45	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1
46	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1
47	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1
48	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1
49	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1
50	0·04	11	0·00	11	5·04	11	23	3	0	1	11	11	3	1

Example 2. In Table III and Fig. 1 are presented the OSA prediction values for the time series from Table I in common with the corresponding active statements of the linguistic model. The prediction starts without any statement. According to the model (*10*), the statements are presented in transposed vector form with elements Y, X, U_1, and U_2.

As for purely linguistic evaluation, the model, consisting of 17 statements, exhibits the perfect accordance between experimental data and their OSA prediction. The numerical accuracy is given (as has been said before) by the number of discrete elements in universa and the number of linguistic terms in evaluating scales. To demonstrate the increase in accuracy of OSA prediction due to the increased density of discrete nets of universa and evaluating scales, the number of numerical elements in the universa of Y, X, U_1 and U_2 is now 21 and so it is also with the number of evaluating terms. The model and control results are summarized in Table IV and Fig. 2. It is to be emphasized that these increased claims for computer memory are still acceptable even for purely control purposes.

The slight activity of acid pump after attaining the set-point (pH 5) faces the higher pH value of water as an inert material. The OSA prediction is based on the linguistic model only. Possible differencies between the statements and corresponding actual activities of the pumps are caused by the specific role of acceleration and damping parameters of the FLC (ref.[2]).

As seen from Table IV, the static gain for the set-point pH 5 is approximately $23/0{\cdot}05 = 460$ mV for the acid pump and 0 mV for the alkali pump, i.e. $\mathrm{SG}(1, K) = 3$ with $\mathrm{sign}\,(\mathrm{SU}(1, K)) = +1$ and $\mathrm{SG}(2, K) = 1$ with $\mathrm{sign}\,(\mathrm{SU}(2, K)) = -1$. Thus the formation of conditional statements of the controller's model is made according to the couple of logical premises

$$[\mathrm{X}(K) \geqq 5] \text{ and } [\mathrm{MS}(3, L) \geqq 3]$$
$$[\mathrm{X}(K) \leqq 5] \text{ and } [\mathrm{MS}(3, L) \leqq 3] \qquad (13)$$

for the acid pump and

$$[\mathrm{X}(K) \geqq 5] \text{ and } [-\mathrm{MS}(4, L) \geqq -1]$$
$$[\mathrm{X}(K) \leqq 5] \text{ and } [-\mathrm{MS}(4, K) \leqq -1] \qquad (14)$$

for the alkali pump. It is quite easy to check TRUE value of the premises (*13*), (*14*) for all statements of the model in the time-series in Table IV.

CONCLUSIONS

As a rule, fuzzy models and especially fuzzy controllers have been understood as proper tools for modelling and control in situations when the fuzzy approach is appropriate. The word "appropriate", fuzzy in its nature, is very often mistaken for "approximate", "inaccurate", etc. As up to now obtained experience shows, there are several situations where fuzzy approach may be taken even as proper and convenient. Process control serves as an example[1-3].

The pH control, illustratively mentioned in the paper, has been not selected by chance. Such a system is usually considered as rather difficult to control with accuracy. The approach with fuzzy-logic controller, including the linguistic description and identification of the system, proves itself succesful and reliable even in comparison with conventional controllers[2]. The only problem is in an acceptable density of universa and evaluating scales of the variables of the model.

The big advantage of the fuzzy-linguistic approach is given by its relative simplicity in description and identification of the structure in question. Though non-numerical in its primary understanding and nature, the quantisation according to the corresponding numerical axes and term-sets enables to obtain the desired output in fully quantitative form. The possibility of combining linguistic and numerical variables in hybrid forms is preserved.

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Translated by the author (J.V.).