Mechanical Properties Evaluation for Pneumatic Actuator and Electric Actuator Based on AHP-FCE

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***Abstract*—The actuators' mechanical properties evaluation is a fuzzy concept with multiple properties and classes. The fuzzy data quantification, analytic hierarchy process and fuzzy comprehensive evaluation (AHP-FCE) methods are combined to establish the actuators' mechanical properties evaluation (MPE) model. The flowchart of actuators' MPE and selection on AHP-FCE was considered and characterized in detail. The weighted average principle has been taken to replace the maximum membership principle in dealing with the actuator' mechanical properties comprehensive value. One pneumatic actuator and one electric actuator in same working demand are taken as an example to verify the evaluation model. The result shows that it is effective, correct, easy to apply and worth to being recommended in similar evaluation field.**

Keywords- mechanical properties; evaluation; AHP-FCE; fuzzy relation matrix; pneumatic actuator; electric actuator

I. INTRODUCTION

Pneumatic actuators and electric actuators are all very widely used in automatic production line nowadays. Cylinder driving systems since the1970s in the field of industrialization have been rapidly spread [1]. Cylinders for reciprocating linear motion applies, in particular, applied to the workpiece moving straight occasions. Now, the cylinder has become the mainstream of the actuator in the field of industrial production in PTP (Point To Point) transmission occasions [2]. In recent years, China's annual growth rate of the cylinder volume has been maintained above 20%.

Electric actuators are mainly used for rotating and oscillating conditions. Electric actuators for the linear removal conditions are on the rise in recent years. Electric actuator enables high-precision multi-point positioning, pneumatic actuators is very difficult to achieve. In the selection of actuators, especially in the most PTP transmission occasions of industrial automation, there have not been sufficient data to describe their selection criteria up to now.

There have not been the further research findings on the MPE (Mechanical Properties Evaluation) of actuators up to now.[3] The MPE of actuators is a mechanical multi-criteria decision making problem. Most conceptions of rational decision-making[4,5,6] assume that a decision-maker knows what he or she wants and has accurate information about his or her own abilities, and the state of world[7]. But people are not rational decision-makers[8]. They have varying accuracy in assessing their own skills, often believing themselves to be more skillful than they are [9]. In order to assist people in making better decisions, many researchers have turned to various decision methods and decision support tools [10, 11].

Multi-criteria decision-making (MCDM) literature [12] can be tracked back to the 1960s and earlier [13]. The work on MCDM methods proceeded in parallel with development of methods for applying utility theory[14,15]. All MCDM methods involve making preference decisions over a set of alternatives which are characterized by multiple, usually conflicting, criteria.

The most common multi-object evaluation methods have FCE (Fuzzy Comprehensive Evaluation), AHP (Analytic Hierarchy Process), gray correlation analysis, the weighted average method and so on. In these methods, mathematic model of FCE can be established by actuators' mechanical properties and their relation. In the FCE method, the weight of indexes is very difficult to determination [16]. AHP can be used for simple

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comprehensive evaluation problem from both qualitative and quantitative factors, but it need extra time [17].

The AHP involves the use of a hierarchical structure to represent the decision problem. In AHP, it is useful for incorporate judgments on intangible qualitative criteria alongside tangible quantitative criteria[18]. The AHP is a well-known method in multi-criteria decision making and there are many articles and books describing the method and its application [19,20,21,22,23]. The AHP need decision maker compare each pair of alternatives and determine which one is preferable and by how much. The AHP method resulted in a higher between decision makers' judgments. Users do not feel that the method used caused decision makers to agree or disagree for reasons that will be discussed in more detail in later selection. In this case, the decision makers did, in general, tend to agree on which products represented the best applicants. However, we explain the higher level of agreement when using AHP as being due to the greater amount of information elicited by the AHP method, resulting in a more accurate reflection of decision maker's preferences[24].

Although AHP needs extra time and has some inconvenience, the Analytic Hierarchy Process may be more appropriate in high criticality tasks, such as medical diagnosis or military planning, where the consequences of decisions may be catastrophic. Whether can AHP be applied to the FCE of actuators mechanical properties for the mechanical properties weight? For the evaluation and selection of actuators, whether can it be solved with AHP-FCE? How to solve the problem with AHP-FCE? These problems have not been studied deeply up to now.

This paper proposed the mechanical multi-attribute evaluation method of the pneumatic & electric actuators based on AHP-FCE. For the same working conditions of pneumatic actuators and electric actuators, mechanical properties parameter table of the two kinds of actuators was established. AHP-FCE method for the actuators MPE is very easy and can be quickly operated to select the better object. Evaluation and selection of similar electromechanical products can also use this objectivity method to compare them quickly.

II. Description of Actuators' Mechanical Properties Evaluation

Pneumatic actuators are widely used in water treatment, chemical industry, automation control industry. Pneumatic actuator can't work without compressed air. When pneumatic actuator reciprocates linear motion, it will consume compressed air which is produced by compressors. Compressors consume some electricity and exhaust a certain amount of compressed air. The production of compressed air can be one of the expensive processes in the manufacturing facilities. Pneumatic actuator can't work normally if there are not compressors, after coolers, receivers, air filters, solenoid valves and governor valves and so on[25].

The production of compressed air can be one of the expensive processes in the manufacturing facilities. Pneumatic actuators' consumption of compressed air is at a cost. And compressed air loss in pipeline network will eventually become heat emissions into the atmosphere [26].

Common pneumatic actuator application field is described as the following Fig. 1.

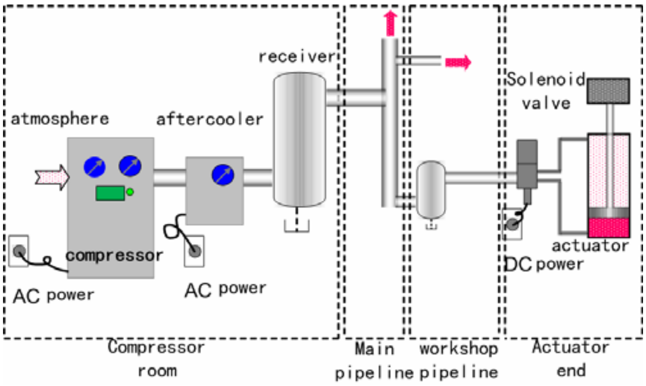

Figure 1. Common pneumatic actuator application field

Electric actuator consumes electricity directly. Electric actuator transits workpiece from one point to the other according to the control signal of PC, PLC or special controller. Servo motor and controller are the main energy-consumption parts.

Configuration of electric reciprocating actuator is shown as the following Fig. 2.

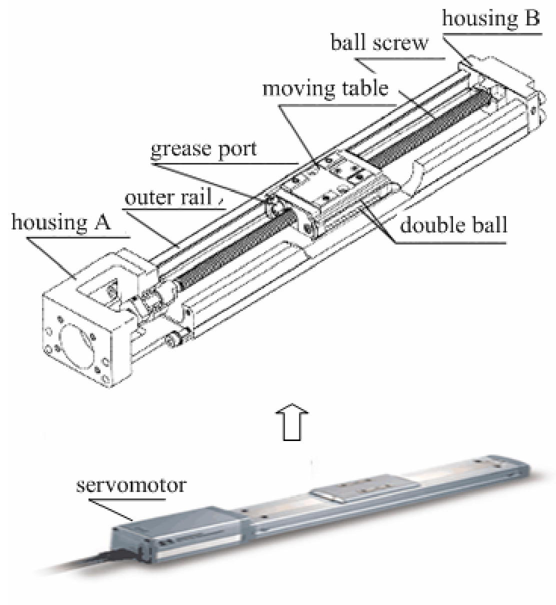

Figure 2. Configuration of electric reciprocating actuator

Pneumatic actuators and electric actuators have a lot of mechanical properties, such as mass, volume, load capacity, work stroke, speed, positioning accuracy etc. When in actuator solution selection , actuator needs to satisfy the actual working condition and is considered from work trip, load capacity, mass, volume, speed, running power, power density ratio (the ratio of operating power and density), as well as life, positioning accuracy and other factors[27]. Among these properties, mass, volume, running power, power density ratio, positioning accuracy are cost-type properties (contrarian indicator), such as the mass property, the lighter the better. Work trip, load capacity, speed, life was efficiency-type properties (positive indicators), such as the life property, the longer it is, the better it is [28].

Evaluation of mechanical properties of the actuator in mathematics belongs to multi-objective decision-making problem. Fig.3 shows the multi-objective solution selection hierarchy of pneumatic actuator and electric actuator.

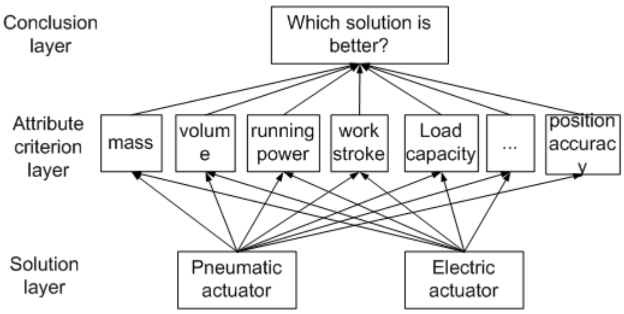

Figure 3. Example of actuators' multi-objective solution selection hierarchy.

Multi-objective (attribute) decision-making problem can be described as: Given a solution sets M, $M=[M_1, M_2, \ldots, M_p]^T$, each solution M_i, $M_i=[m_{i1}, m_{i2}, \ldots, m_{in}]$, as in

$$M=\begin{bmatrix} M_1 & M_2 & \cdots & M_p \end{bmatrix}^T=\begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{21} & m_{22} & \cdots & m_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m_{p1} & m_{p2} & \cdots & m_{pn} \end{bmatrix}_{p\cdot n} \tag{1}$$

The evaluation aim is to select the most appropriate solution through a series of evaluation strategies from the solution sets [24].

III. ESTABLISHMENT OF ACTUATORS' MPE MOEDL BASED ON AHP-FCE

In the MPE model about AHP-FCE presented in this paper, an attempt is made to combine the multi-criteria decision making theories with the theory of fuzzy sets.

Actuators, when in the solution selection, need to satisfy the actual working condition, and are considered from work trip, load capacity, mass, volume, speed, running power, power density ratio (the ratio of operating power and density), as well as life, positioning accuracy and other factors[25].

Fig. 4 shows the flowchart of actuators' MPE and selection on AHP-FCE. According to actuators' actual working requirements and experts' application experience, mechanical performance evaluation indexes of set pneumatic actuators & electric actuators were determined as shown in Table I. And actuators' evaluation ratings were also defined as shown Table II. Then the weights of the evaluation indexes were gained through Saaty's 1-9 scale method and AHP. Through the normalization method, these weights were mapped to a certain value of [0, 1]. And afterwards fuzzy relation matrix was set up by the quantitative result of actuators according to evaluation indexes set [28]. Then fuzzy comprehensive evaluation results vector were calculated with indexes' weight vector and fuzzy relation matrix. Finally, the comprehensive value of each actuator was calculated by the AHP-FCE algorithm and the final ranking was also figured out [29].

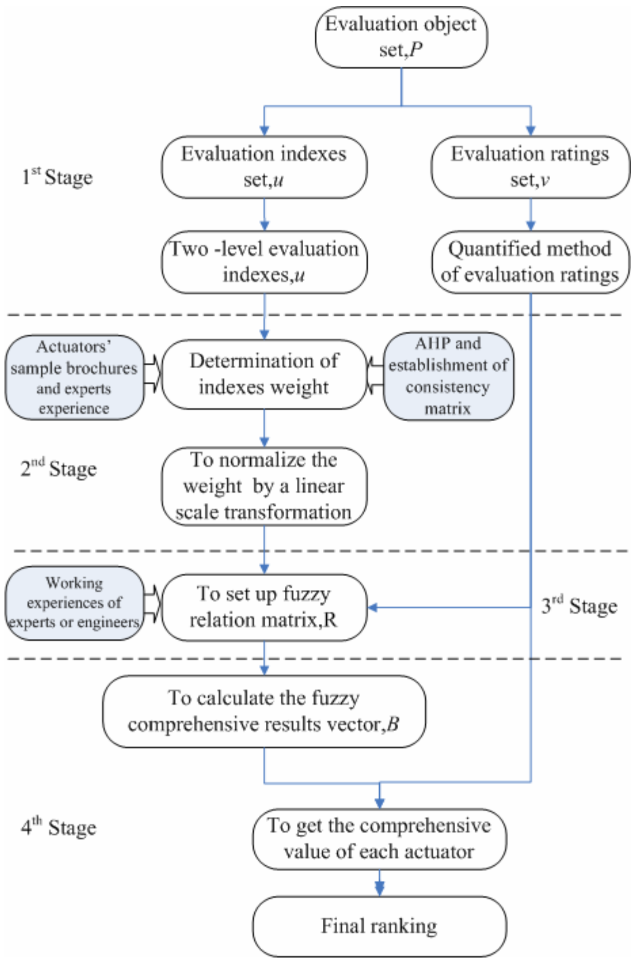

Figure 4. Flowchart of actuators MPE and selection based on AHP-FCE.

Determination of Actuators' Mechanical Performance Evaluation Indexes and Evaluation Ratings

Through actuators' sample brochures, the pneumatic actuators and electric actuators suitable for these requirements are selected. These actuators are analyzed as evaluation objects. Evaluation objects are defined as

$$P=\{p_1, p_2, \cdots, p_n\} \tag{2}$$

where P is evaluation objects sets, p_i is the element of the sets.

Then evaluation indexes were determined by experts' working experiences. These indexes are defined as

$$u=\{u_1,u_2,\cdots,u_n\} \tag{3}$$

where u is evaluation indexes sets, u_i is the element of the sets.

Through the analysis of mechanical properties of the actuators, common pneumatic actuators and electric actuators was recognized as research object and their mechanical performance evaluation indexes was made up of two levels. As shown in Table I, there were six first-level indexes and sixteen second-level indexes.

First-level indexes were listed as in Table I:

$u=\{u_1,u_2,u_3,u_4,u_5,u_6\}$ = {Physical characteristics, Working scope, Assembly operation, Actuation characteristics, Power characteristics, Reliability}.

Second-level indexes were also listed as in Table I:

$u_1=\{u_{11},u_{12}\}$ = {Actuators mass, Actuators volume}.

$u_2=\{u_{21},u_{22},u_{23}\}$ = {Working stroke, Horizontal load, Vertical load}.

$u_3=\{u_{31},u_{32},u_{33}\}$ = {Installation difficulty, Ease to use }.

$u_4=\{u_{41},u_{42}\}$ = {Positioning accuracy, Speed}.

$u_5=\{u_{51},u_{52},u_{53},u_{54}\}$ = {Operating power, Load to maintain power, No-load power consumption, Consumption power density ratio}.

$u_6=\{u_{61},u_{62},u_{63}\}$ = {Easy to maintenance, Maintenance cycle, Life span}.

Afterwards evaluation ratings were also determined by experts' working experience. And the ratings were quantified according to a certain proportion as shown in Table II.

TABLE I. ACTUATORS TWO-LEVEL COMPREHENSIVE EVALUATION INDEXES AND WEIGHT

Comprehensive index	Weight	Evaluation indexes	Weight
Physical characteristics	0.036	Actuators mass	0.250
		Actuators volume	0.750
Working scope	0.321	Working stroke	0.467
		Horizontal load	0.333
		Vertical load	0.200
Assembly operation	0.250	Installation difficulty	0.300
		Ease to use	0.700
Actuation characteristics	0.107	positioning accuracy	0.417
		speed	0.583
Power characteristics	0.179	Operating power	0.333
		Load to maintain power	0.259
		No-load power consumption	0.111
		Consumption Power density ratio	0.296
Reliability	0.107	Easy to maintenance	0.333
		Maintenance cycle	0.200
		Life span	0.467

TABLE II. STANDARD OF QUANTITATIVE EVALUATION GRADES

Value	remark	assignment	grade
$x_i>3.5$	Optimal	4	A
$3.5\geq x_i>2.5$	Good	3	B
$2.5\geq x_i>1.5$	Middle	2	C
$x_i\leq 1.5$	Bad	1	D

Actuators' Indexes Weight Calculation Based on AHP

With Saaty's 1-9 scale method, a judgment matrix S was constructed for the six first-level indexes.

$$S=\begin{bmatrix} 1 & \frac{1}{9} & \frac{1}{7} & \frac{1}{3} & \frac{1}{5} & \frac{1}{3} \\ 9 & 1 & \frac{9}{7} & 3 & \frac{9}{5} & 3 \\ 7 & \frac{7}{9} & 1 & \frac{7}{3} & \frac{7}{5} & \frac{7}{3} \\ 3 & \frac{1}{3} & \frac{3}{7} & 1 & \frac{3}{5} & 1 \\ 5 & \frac{5}{9} & \frac{5}{7} & \frac{5}{3} & 1 & \frac{5}{3} \\ 3 & \frac{1}{3} & \frac{3}{7} & 1 & \frac{3}{5} & 1 \end{bmatrix} \tag{4}$$

When S was constructed, actuators application experts considered the importance of each index in first column and rated the mark from 1 to 9. Then the values of other columns in matrix S could be deduced because matrix S was the diagonal matrix. With this method, matrix S could be easily gained. Matrix S was proved that it was the consistent matrix through mathematical proof. And the number of consistent matrix eigenvalue was matrix's columns or matrix's rows (consistent matrix was the square matrix.).

Matrix S's eigenvalues were the weights of six first-level indexes .They were gained and mapped to a certain value of [0, 1] as follows.

$$\begin{aligned}\omega &= (\omega_1,\omega_2,\omega_3,\omega_4,\omega_5,\omega_6) \\ &= (0.036, 0.321, 0.250, 0.107, 0.179, 0.107)\end{aligned} \tag{5}$$

The weights of second-level indexes were also easily gained with above method. These weights data were shown as follows.

$$\omega_1' = (\omega_{11},\omega_{12}) = (0.250, 0.750) \tag{6}$$

$$\omega_2' = (\omega_{21},\omega_{22},\omega_{23}) = (0.467, 0.333, 0.200) \tag{7}$$

$$\omega_3' = (\omega_{31},\omega_{32}) = (0.300, 0.700) \tag{8}$$

$$\omega_4' = (\omega_{41}, \omega_{42}) = (0.417, 0.583) \quad (9)$$

$$\omega_5' = (\omega_{51}, \omega_{52}, \omega_{53}, \omega_{54}) = (0.333, 0.259, 0.111, 0.296) \quad (10)$$

$$\omega_6' = (\omega_{61}, \omega_{62}, \omega_{63}) = (0.333, 0.200, 0.467) \quad (11)$$

Establishing the fuzzy relation matrix R

With the standard of quantitative evaluation grades in Table II, actuators were quantified from each index, i.e. to determine the actuators' membership degree of evaluation grades from each factor. Therefore, actuators' performance in some index was characterized through fuzzy vector $(R|u_i)=(r_{i1},r_{i2},\cdots,r_{im})$ with FCE. However other methods often use one definitive value to characterize things. The fuzzy relation matrix R was defined as:

$$R = \begin{bmatrix} R| & u_1 \\ R| & u_2 \\ & \vdots \\ R| & u_n \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}_{n\cdot m} \quad (12)$$

where R is the fuzzy relation matrix, u_i is the element of evaluation indexes sets. r_{ij} was the grade that actuators application experts evaluated.

Calculating Actuator's FCE Result Vector and Final Comprehensive Evaluation Value

The weight average operator M(+,•) had been introduced, which took ''+'' and ''•'' to replace ''∨'' and ''∧'', respectively[9].Therefore, with AHP-FCE, the actuator's FCE result vector B was obtained through the following equations:

$$B = \omega \cdot R = (\omega_1, \ \omega_2, \cdots, \ \omega_n) = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \quad (13)$$
$$= (b_1, b_2, \cdots b_m)$$

$$b_j = \min\left(1, \sum_{i=1}^{n} (\omega_i \times r_{ij})\right), \ j = 1, 2, \cdots, p \quad (14)$$

The weighted average principle was applied to replace the maximum membership principle, so all experts evaluation information would be reserved in the evaluation vector as much as possible. The actuator's final comprehensive evaluation value F could be gained with the following equation:

$$F = B \cdot G = B \cdot \begin{pmatrix} 4 \\ 3 \\ 2 \\ 1 \end{pmatrix} = 4 \times b_1 + 3 \times b_2 + 2 \times b_3 + 1 \times b_4 \quad (15)$$

where G is the matrix of quantitative evaluation standard grades.

Finally these actuators' final ranking can be gained through sorting the FCE final comprehensive evaluation value F from big to small.

IV. CASE STUDY

Pneumatic actuators and electric actuators to be selected must satisfy the actual working requirements when we select pneumatic actuators or electric actuators to transport workpiece.

The actual workpiece flitting conditions in the automatic line in a manufacture factory (e.g.) are:

1) Flitting workpiece mass on the horizontal is 5 kilograms.
2) Flitting workpiece mass on the vertical is 2 kilograms.
3) Working stroke is 30mm
4) Reciprocating working frequency is 1~50 times per minute.

According to the working condition of actuators above all, pneumatic and electric actuators are selected. These actuators' mechanical properties are shown in table III:

TABLE III. MECHANICAL PROPERTIES OF PNEUMATIC ACTUATOR AND ELECTRIC ACTUATOR TO BE SELECTED

	Pneumatic actuator	Electric actuator
Type	CDJ2B10-30A	RCS2-RA4C-A-20-6-50-T2-S
Mass/kg	0.06	1.1
Volume/dm3	1.50	75.00
Work stroke /mm	30	50
Horizontal load/kg	5.5	6
Vertical load/kg	4.6	2
Positioning accuracy/mm	$^{+1.0}_{0}$	±0.02
Speed/m/s	50-750	300
Horizontal running power /W	7.03	9.58
Vertical running power /W	6.55	10.17
Horizontal power density ratio/W/dm3	1.76	6.53

Vertical power density ratio/W/dm3	1.63	6.93
Repairing	Easy repairing, short time	Difficult repairing, long time
Working life/km	5000	5000

Mechanical properties of the two kinds of actuators were obtained from their sample books, experts' working experience and fluid mechanics knowledge.

Second-level fuzzy relation matrixes of pneumatic actuator

Second-level fuzzy relation matrixes *R* of pneumatic actuators were listed as the following.

$$R_{p1}=\begin{Bmatrix}0.417 & 0.333 & 0.167 & 0.083\\ 0.429 & 0.357 & 0.143 & 0.071\end{Bmatrix}$$

$$R_{p2}=\begin{Bmatrix}0.294 & 0.471 & 0.176 & 0.059\\ 0.467 & 0.400 & 0.100 & 0.033\\ 0.471 & 0.412 & 0.088 & 0.029\end{Bmatrix}$$

$$R_{p3}=\begin{Bmatrix}0.633 & 0.267 & 0.067 & 0.033\\ 0.685 & 0.210 & 0.070 & 0.035\end{Bmatrix}$$

$$R_{p4}=\begin{Bmatrix}0.111 & 0.278 & 0.444 & 0.167\\ 0.086 & 0.171 & 0.514 & 0.229\end{Bmatrix}$$

$$R_{p5}=\begin{Bmatrix}0.381 & 0.429 & 0.143 & 0.048\\ 0.442 & 0.372 & 0.140 & 0.047\\ 0.720 & 0.160 & 0.080 & 0.040\\ 0.333 & 0.429 & 0.143 & 0.095\end{Bmatrix}$$

$$R_{p6}=\begin{Bmatrix}0.486 & 0.432 & 0.054 & 0.027\\ 0.474 & 0.447 & 0.053 & 0.026\\ 0.375 & 0.438 & 0.125 & 0.063\end{Bmatrix}$$

Second-level FCE result matrixes of pneumatic actuator

Pneumatic actuator second-level FCE result vectors B_p were listed as the following.

$$B_{p1}=\omega_1'\cdot R_{p1}=(0.426,0.351,0.149,0.074) \quad (16)$$

$$B_{p2}=\omega_2'\cdot R_{p2}=(0.387,0.435,0.133,0.044) \quad (17)$$

$$B_{p3}=\omega_3'\cdot R_{p3}=(0.657,0.227,0.069,0.034) \quad (18)$$

$$B_{p4}=\omega_4'\cdot R_{p4}=(0.092,0.216,0.485,0.203) \quad (19)$$

$$B_{p5}=\omega_5'\cdot R_{p5}=(0.420,0.384,0.135,0.061) \quad (20)$$

$$B_{p6}=\omega_6'\cdot R_{p6}=(0.432,0.438,0.087,0.043) \quad (21)$$

First-level FCE result vectors of pneumatic actuator was gained as the following.

$$B_p=\omega\cdot R=\omega\cdot\begin{pmatrix}B_{p1}\\ B_{p2}\\ \vdots\\ B_{p6}\end{pmatrix}=(0.439,0.348,0.151,0.063) \quad (22)$$

Pneumatic actuator final comprehensive evaluation value was calculated as the following.

$$F_p=4\times0.439+3\times0.348+2\times0.151+1\times0.063=3.162 \quad (23)$$

Therefore the grade of pneumatic actuator was ranked "B".

Second-level fuzzy relation matrixes of electric actuator

Similarly with pneumatic actuator, second-level fuzzy relation matrixes *R* of pneumatic actuators were listed as the following.

$$R_{e1}=\begin{Bmatrix}0.065 & 0.129 & 0.548 & 0.258\\ 0.069 & 0.138 & 0.552 & 0.241\end{Bmatrix}$$

$$R_{e2}=\begin{Bmatrix}0.259 & 0.667 & 0.074 & 0.000\\ 0.514 & 0.457 & 0.029 & 0.000\\ 0.118 & 0.353 & 0.412 & 0.118\end{Bmatrix}$$

$$R_{e3}=\begin{Bmatrix}0.056 & 0.111 & 0.444 & 0.389\\ 0.056 & 0.167 & 0.333 & 0.444\end{Bmatrix}$$

$$R_{e4}=\begin{Bmatrix}0.389 & 0.500 & 0.111 & 0.000\\ 0.158 & 0.263 & 0.474 & 0.105\end{Bmatrix}$$

$$R_{e5}=\begin{Bmatrix}0.056 & 0.167 & 0.500 & 0.278\\ 0.059 & 0.235 & 0.471 & 0.235\\ 0.050 & 0.100 & 0.800 & 0.050\\ 0.077 & 0.308 & 0.385 & 0.231\end{Bmatrix}$$

$$R_{e6}=\begin{Bmatrix}0.048 & 0.143 & 0.429 & 0.381\\ 0.026 & 0.103 & 0.462 & 0.410\\ 0.091 & 0.182 & 0.455 & 0.273\end{Bmatrix}$$

Second-level FCE result matrixes of electric actuator

Electric actuator second-level FCE result vectors B_e were listed as the following.

$$B_{e1}=\omega_1'\cdot R_{e1}=(0.068,0.136,0.551,0.246) \quad (24)$$

$$B_{e2} = \omega_2' \cdot R_{e2} = (0.316, 0.534, 0.126, 0.024) \quad (25)$$

$$B_{e3} = \omega_3' \cdot R_{e3} = (0.056, 0.150, 0.367, 0.428) \quad (26)$$

$$B_{e4} = \omega_4' \cdot R_{e4} = (0.254, 0.362, 0.322, 0.061) \quad (27)$$

$$B_{e5} = \omega_5' \cdot R_{e5} = (0.062, 0.219, 0.492, 0.228) \quad (28)$$

$$B_{e6} = \omega_6' \cdot R_{e6} = (0.063, 0.153, 0.447, 0.336) \quad (29)$$

Pneumatic actuator final comprehensive evaluation value was calculated as the following.

$$F = 4\times 0.163+3\times 0.308+2\times 0.322+1\times 0.207 = 2.427 \quad (30)$$

Finally the grade of electric actuator was ranked “C”.

AHP-FCE result of pneumatic and electric actuator

With above AHP-FCE method and data of actuators, the results showed that the comprehensive performance of the pneumatic actuator is better than one of the electric actuator in this actual working condition.

In other working condition, we can also choose out the better actuator in a very large number of pneumatic and electric actuators by the actuator AHP-FCE analysis method.

V. Conclusions

In this paper, the fuzzy data quantification and AHP-FCE methods are combined to establish the actuators’ mechanical properties evaluation (MPE) model. The flowchart of actuators’ MPE and selection on AHP-FCE was considered and characterized in detail. In addition, the weighted average principle has been taken to replace the maximum membership principle, so the information will be reserved in the evaluation coefficients as much as possible for improving the evaluation accuracy. Finally the actuators’ MPE model on AHP-FCE is verified with an actual application case to prove its accuracy.

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