The Design of the Controlling Cam Optimization Profile in an Automated-Cutoff Valve Based on Ga

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Abstract. In order to achieve the controlling performance of automated-cutoff valve, an optimization method of cam profile design is indicated based on GA. The selection conditions in the algorithm are established according to the analysis of mechanical structure after the other parameters are specified. The effectiveness of the optimization algorithm is improved in the sequent test.

Keywords: optimization;GA;control device.

1. Introduction

The leakage of natural gas which is one of the most important clearer energy in modern life usually has a tendency of destructive consequence. The danger will be reduced by the assembling of automated-cutoff valve in the pipe system, which can cut off the gas supply when the abnormal pressure or flow is tested. The valves with pure mechanical structure show outstanding performance than the ones based on the electronic or magnetic fundamentals in the view of reliability and endurance.

The controlling mechanism of an automated-cutoff valve illustrated in Fig 1(a) is composed of a pole with a cover and a cam fixed with a rubber gasket at the end. The cam will move at the velocity v2 in Fig 1(b) because of the deformation of gasket induced by the change of pressure in the valve originated from abnormal gaseous pressure or flow. When the cam reaches the position shown in Fig 1(b), the pole pushed by a spring will shift at velocity v1 until get to the position shown in Fig 1 (c), where the cover blocks the pipe and gas supply is cut off. The pole can shift back to the original position in Fig 1 (a) by the cam pulled by hand opposite to the direction of v2 after the fluid field in the valve recovers to the normal situation.

The mechanism should be designed at the requirement that the pole shifts as quickly as possible (achieves the displacement in less than 0.6s) with the less impact and free of self-locking, which depends on the profile of segment AB on the cam mostly. The method of optimized design of a cam profile has been study by many scholars. Some of them obtained the ideal profile depending on the analysis of movement process. Cai analyzed the causes and influence of cam angle offset and proposed a model to realize precise mapping of cam parameters to contour curve[1]. Yue designed the ideal working profile of a cam based on calculation after extracted three key parameters affecting the kinematics performance[2]. XU discreted the putter profile after the study of its movement, generated multiple curves and took the intersection operation. Then the ideal cam profile is obtained[3]. SU established a parameter equation for the cam profile according to the selected actuator motion rules, which leaded to the cam contour curve calculated with motion parameters by computer[4]. GU designed the cam profile curve meeting the expected motion requirements of the cam follower by using SolidWorks motion[5]. LI obtained the mathematical model of the curved cam working surface derived from kinetics and envelope theory[6]. ZHENG achieved the design work with an analytical method of envelope and transient laws[7]. Instead of analysis on motion itself, other studies emphasis on the change of force exerting on the cam profile. DENG established the curve equation of cam profile after the research on the relation about cam parameters and the output force[8]. HU optimized the cam profile curve with resistance torque through dynamic simulation on contact force[9]. CHENG calculated the profile parameters with the principle of equivalent power after determining the output force characteristics. Then the cam profile curve was fitted[10].

These methods are workable on condition that the motion of the cam can be controlled by users precisely. However,the detailed motion of the cam in the automated-cutoff valve is unknown because of the pole velocity can't be influenced at any time artificially. The optimization scheme with reference to GA(genetic algorithm) is proposed to solve such issue when a reasonable selection criterion with special algorithm is achieved[9][10][11]. Therefore,the effective selection function for the control device in the valve is indicated in this paper with detailed algorithm, in which the parameters expressed in the equation for the cam curve are acquired by crossover and mutation in populations and excellent individuals are selected by performance norm according to the mechanical characters analyzed in part 2. Moreover, a validating test for the optimized curve is accomplished.

2. The Mechanical Model of the Control Device

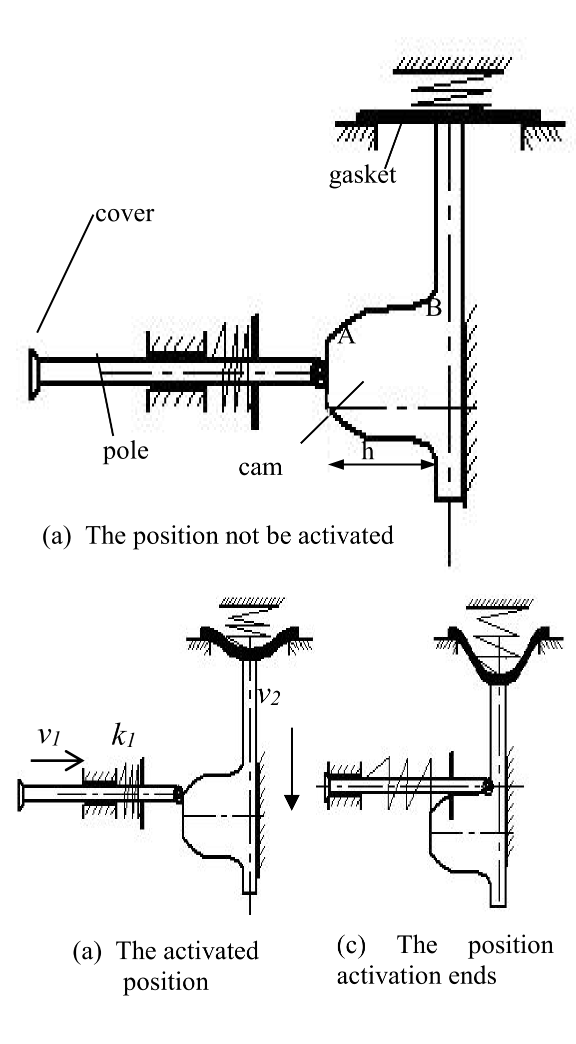

Fig 1. The controlling mechanism in an automated-cutoff valve

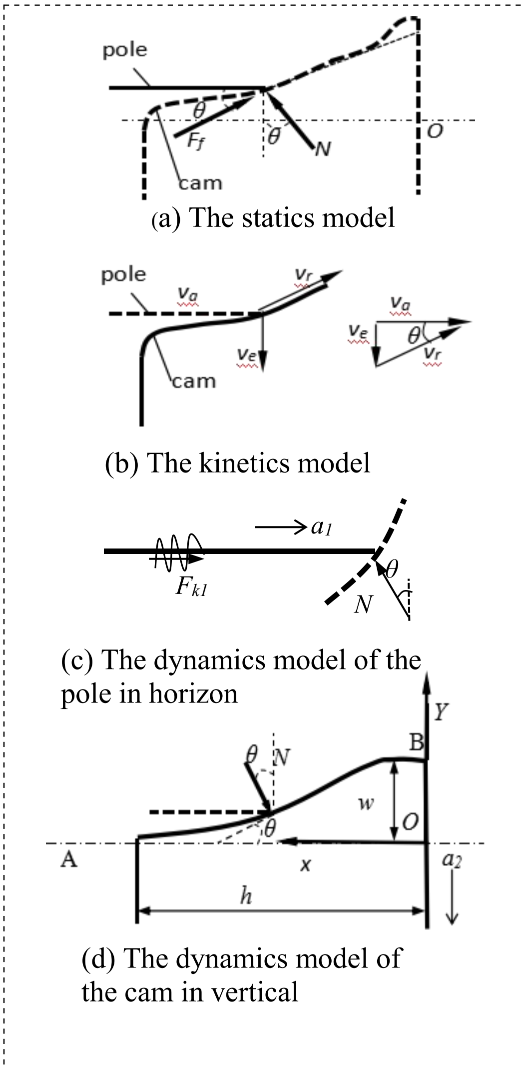

Fig 2. The mechanical model of cam device

Considering the cost and manufacturing , the contour curve of AB segment on the cam is preferred to be expressed by the function of a fourth order interpolation polynomial, which can be expressed by Equ (1) as follows according to the coordinates in Fig 2 (d).

$$y = g(x) = a_4x^4 + a_3x^3 + a_2x^2 + a_1x + w \quad (1)$$

2.1 The static model

When the condition belows is met, the device will be free of self-locking after study the statics model in Fig 2 (a).

$$N\sin\theta > F_f\cos\theta ,$$

Here N is the force exerting on the pole from the cam and Ff is the corresponding friction. So

$$tg\theta > \mu ,$$

Where μ is the friction coefficient. Namely the following equation is obtained because The tangent of the angle θ is from the derivative of the curve y with respect to x.

$$g'(x) = 4a_4x^3 + 3a_3x^2 + 2a_2x + a_1 = tg(\pi-\theta) < -\mu \quad (2)$$

2.2 The kinetics model of the cam device

The relationship of velocities in the device motion in Fig 2(b) can be expressed as follows：

$$\vec{v}_a = \vec{v}_e + \vec{v}_r$$

Namely, $v_e = v_a tg\theta$

Comparing Fig 1(b) and Fig 2(b), it is obvious that v1 = va and v2 = ve。Therefore, $v_2 = v_1 tg\theta$

Taking the derivative of both side, then,

$$\dot{v}_2 = a_2 = a_1 tg\theta + v_1^2\frac{dtg\theta}{dx} = a_1 tg\theta + v_1^2 tg'\theta \quad (3)$$

2.3 The dynamics model of the cam device

From the Fig 2(c) and (d), the following equation can be achieved, in which the effects of friction are ignored due to the fact that the device has been designed as the mechanism with rolling friction, the energy exhausted by which can be ignored:

$$\begin{cases} m_1a_1 = k_1x - N\sin\theta \\ m_2a_2 = N\cos\theta \end{cases}$$

Where m1 and m2 are the mass of them respectively while k1 is the spring stiffness. Therefore,

$$m_1a_1 = k_1x - m_2a_2tg\theta \quad (4)$$

Substitute Equ (3) to (4) , it is $m_1a_1 = k_1x - m_2(a_1tg\theta + v_1^2tg'\theta)tg\theta$ (5)

Let $D_1(x) = \frac{k_1}{m_1 + m_2tg^2\theta}$, $D_2(x) = \frac{m_2tg\theta tg'\theta}{m_1 + m_2tg^2\theta}$, then $a_1 = D_1(x)x - D_2(x)v_1^2$ (6)

3. The controlling model and the solving methods

In order to identify the rationality of curve design on the cam profile, the motion time tf , during which the pole is shifting from the point x=h to the one x=0, should be computed inevitably. Consequently, the model on the basis of controlling theory has been established.

3.1 The control model and its linearization

According to Equ (6) the controlling model is available as follows easily :

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= D_1(x_1)x_1 - D_2(x_1)x_2^2 \end{aligned} \quad (7)$$

Where x1=x，x2=v1.

Considering the difficulty in the solution of un-linear differential equation, the calculation of the numeric solution is studied instead of the algebraic one.

Suppose the pole moves to the point x1=x1i（i=0,1,...n，x1n= 0<x1n-1<...<x11<x10=h）with the velocity x2=x2i when t=ti . The Equ (7) can be linearized to

$$\begin{aligned}\dot{x}_1 &= x_2 \\ \dot{x}_2 &= d_{1i}x_1 - d_{2i}x_2\end{aligned} \tag{8}$$

Where $d_{1i} = [\frac{dD_1(x_1)}{dx_1}x_1 + D_1(x_1) - \frac{dD_2(x_1)}{dx_1}x_2^2]|_{\substack{x_1=x_{1i}\\x_2=x_{2i}}}$ $\quad d_{2i} = 2D_2(x_1)x_2|_{\substack{x_1=x_{1i}\\x_2=x_{2i}}}$

3.2 The solution of the motion time tf

The following expression is available after the Equ (8) is solved.

$$\begin{cases} x_1 = \frac{c_{1i}}{d_{1i}}(r_{1i}+d_{2i})e^{r_{1i}t} + \frac{c_{2i}}{d_{2i}}(r_{2i}+d_{2i})e^{r_{2i}t} \\ x_2 = c_{1i}e^{r_{1i}t} + c_{2i}e^{r_{2i}t} \end{cases} \tag{9}$$

Where

$$r_{1i} = \frac{-d_{2i}+\sqrt{d_2^2+4d_1}}{2}, \quad r_{2i} = \frac{-d_{2i}-\sqrt{d_2^2+4d_1}}{2}$$

The parameters, c1i and c2i, can be calculated with Equ (10) on condition that x1i and x2i have been known.(10)

$$\begin{aligned} c_{1i} &= \frac{d_{1i}d_{2i}}{r_{1i}d_{2i}+d_{2i}^2-r_{2i}d_{1i}-d_{1i}d_{2i}}(\frac{r_{2i}+d_{2i}}{d_{2i}}x_{2i}-x_{1i}) \\ c_{1i} &= \frac{d_{1i}d_{2i}}{r_{1i}d_{2i}+d_{2i}^2-r_{2i}d_{1i}-d_{1i}d_{2i}}(\frac{r_{1i}+d_{2i}}{d_{1i}}x_{2i}-x_{1i}) \end{aligned} \tag{10}$$

Then the time ti which is spent by the pole shifting from point x1=x1i to the one x1=x1i+1 can be solved according to Equ (11) after linearization at the point x1=x1i with the Equ (12):

$$\frac{c_{1i}}{d_{1i}}(r_{1i}+d_{2i})e^{r_{1i}t_i} + \frac{c_{2i}}{d_{2i}}(r_{2i}+d_{2i})e^{r_{2i}t_i} = x_{1i+1} \tag{11}$$

$$e^{r_{1i}t_i} \approx e^{r_{1i}t_{i-1}} + r_{1i}e^{r_{1i}t_{i-1}}(t_i - t_{i-1}) \qquad e^{r_{2i}t_i} \approx e^{r_{2i}t_{i-1}} + r_{2i}e^{r_{2i}t_{i-1}}(t_i - t_{i-1}) \tag{12}$$

The solution of time t_i is expressed as follows:

$$t_i = \frac{x_{1i+1} + c_{1i}(r_{1i}+d_{2i})e^{r_{1i}t_{i-1}}(r_{1i}t_{i-1}-1)/d_{1i} + c_{2i}(r_{2i}+d_{2i})e^{r_{2i}t_{i-1}}(r_{2i}t_{i-1}-1)/d_{2i}}{c_{1i}(r_{1i}+d_{2i})r_{1i}e^{r_{1i}t_{i-1}}/d_{1i} + c_{2i}(r_{2i}+d_{2i})r_{2i}e^{r_{2i}t_{i-1}}/d_{2i}} \tag{13}$$

And the total time for the pole motion is

$$t_f = \sum_{i=0}^{n-1} t_i \tag{14}$$

while the velocity x_{2i+1} at the point $x_1 = x_{1i+1}$ can also be worked out :

$$x_{2i+1} = c_{1i}e^{r_{1i}t_{i+1}} + c_{2i}e^{r_{2i}t_{i+1}} \tag{15}$$

4. The Optimization Design of the Cam Profile Based on GA

A method on the basis of GA is adopted for the profile optimization of the curve AB on the cam expressed in Equ (1), in which the parameters, a4, a3, a2 and a1 are coded in binary mode as genes on the chromosome while w is determined by the mechanical structure in the valve . Moreover, Roulette Wheel Selection, single point crossover and basic bit mutation are adopted in this study.

4.1 4.1 The calculation of fitness

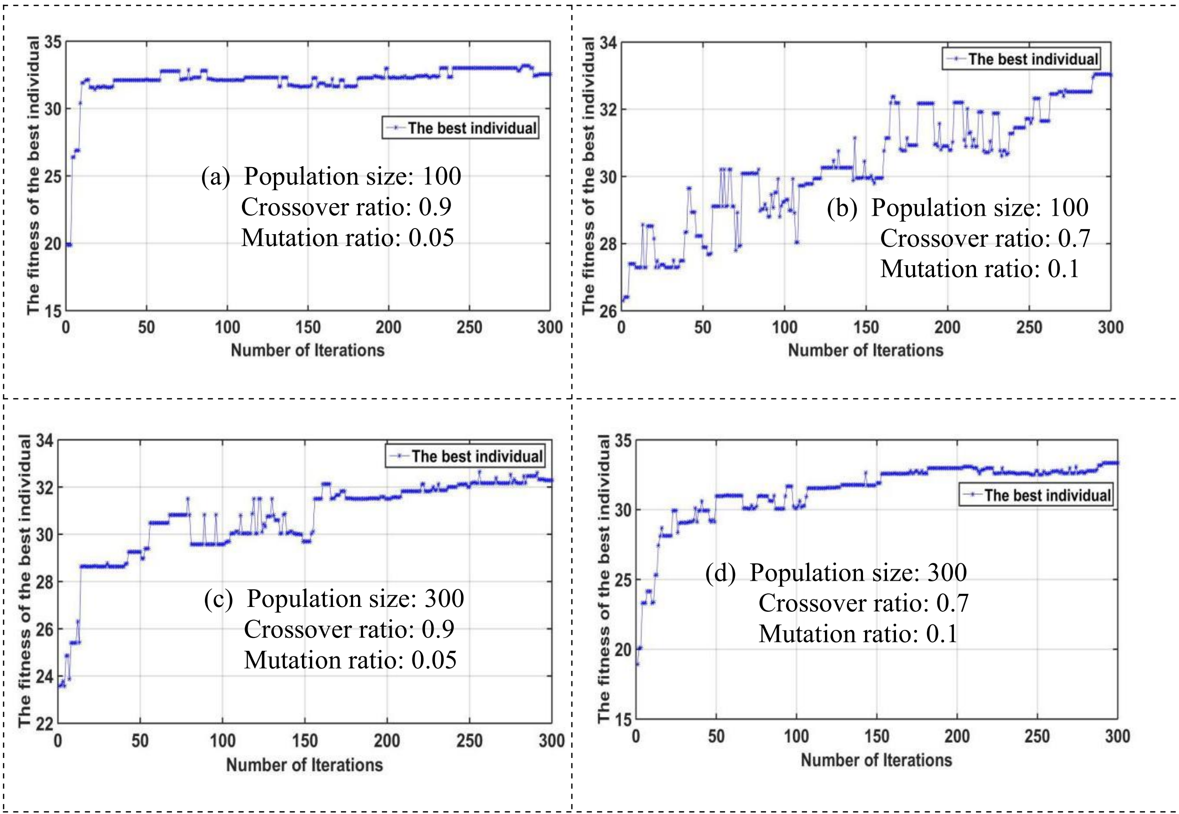

Fig 3. Some iterative processes based GA with different parameters

The least shifting time is expected as well as less impact so that the the performance norm is designed as follows:

$$J = t_f + 0.2\int_0^{t_f} x_2^2 dt \tag{16}$$

the reciprocal of which is regarded as the fitness of a individual in the population, which can be computed in the following detailed steps :

(1) Choose *n-1* points in the interval [h,0] uniformly as $x_{11}, x_{12}, \dots x_{1n-1}$ and specify the value of $x_{10,}\, x_{1n}$ and x_{21} are *h*, 0 and 0 respectively according to the initial and terminal conditions. Specify *i=0* .

(2) Get the approximate linear Equ (8) and it solution expressed by Equ (9) is available.

(3) Work out the value of t_i and x_{2i+1} according to Equ (13) and (15).

(4) Specify *i = i+1* and go back to step (2) until *i=n-1*.

(5) Compute the fitness with Equ (17) based on Equ (16) if Equ (2) is met.

$$F = 1/(\sum_{i=0}^{n-1} t_i + 0.2\sum_{i=0}^{n-1} x_{2i+1}^2 t_i) \tag{17}$$

The fitness is 0 when Equ (2) is not met.

4.2 The optimized result on GA and Validation in testing

It is specified that h is 3mm and w is 6mm in consideration of mechanical structures in this study while m1 ,m2 and k1 are 5 grams, 9 grams and 0.115 N/mm. Some iterative processes based GA are illustrated in Fig 3 with different ratios of crossover and mutation and part of corresponding data are listed in Tab 1. As a result, the best achieved solution of curve AB on the cam in this study is as follows:

$$g(x) = 6 - 1.249x + 0.001x^2 - 0.028x^4$$

In order to validate the result, a test was accomplished and the parameter tf which was from the time that abnormal gas pressure appeared to the one that the click produced by the closing of cover at the end of pole was heard was measured in 20 valves with the optimized curve on their cams. The average value is about 0.51 seconds, which showed the effectiveness of this optimized method of cam profile.

5. Conclusion

The mechanical model about the cam device in a automated-cutoff valve is analyzed in this paper firstly. Then an optimization method of curves with GA on cam profile is demonstrated in the light of performance of this valve with the establishment of the selection norm. Finally the validity of this algorithm has been proved in a test. However, there are still two drawbacks we have to face. One is the error of tf between the value of calculated one and the test one is too obvious to ignored. The other is the iterative optimization process costs too much time with the increase of the parameter n. Further studies are still needed to search for better solutions.

Table 1. Part of the optimized results with different parameters based on GA

Population Number	a_1	a_2	a_3	a_4	tf (s)	The best fitness
Population size: 100 Crossover ratio: 0.9 Mutation ratio: 0.05						
1	-1.2192	0.0056	0.0073	-0.0320	0.325	31.1690
2	-1.1199	0.0073	0.0132	-0.0378	0.322	27.2639
3	-1.2192	0.0056	0.0073	-0.0320	0.314	32.1690
4	-1.0943	0.0283	0.0120	-0.0407	0.354	25.6531
Population size: 100 Crossover ratio: 0.7 Mutation ratio: 0.1						
1	-1.1738	0.0415	0.0146	-0.0401	0.388	32.0457
2	-1.1404	0.0056	0.0188	-0.0387	0.324	27.5745
3	-1.2092	0.0183	0.0022	-0.0321	0.363	30.4484
4	-1.2119	0.0129	0.0237	-0.0385	0.317	31.1023
Population size: 300 Crossover ratio: 0.9 Mutation ratio: 0.05						
1	-1.2482	0.0409	0.0024	-0.0332	0.358	30.4568
2	-1.2409	0.0289	0.0041	-0.0327	0.334	30.8000
3	-1.2314	0.0048	0.0022	-0.0297	0.307	32.1704
4	-1.1741	3.02e-04	0.0241	-0.0387	0.315	28.5199
Population size: 300 Crossover ratio: 0.7 Mutation ratio: 0.1						
1	-1.2411	5.52e-04	5.93e-04	-0.0284	0.301	33.0126
2	-1.2167	0.0467	0.0064	-0.0363	0.358	28.6930
3	-1.2421	0.0091	0.0083	-0.0318	0.288	31.7625
4	-1.2441	0.0107	0.0026	-0.0301	0.299	32.9689

Acknowledge

This paper is supported by Ningbo ‘Science and Technology Innovation 2025’ science and technology project 2020Z109.

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