ATLANTIS PRESS

Advances in Engineering Research, volume 140

2nd International Conference on Electrical, Control and Automation Engineering (ECAE 2017)

A Novel Drive Scheme of Coriolis Mass Flowmeter Based on Adaptive Fuzzy Sliding Mode Control

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***Abstract*—In this paper, a digital-analog drive system based on adaptive fuzzy sliding mode control is developed to improve the performance of the Coriolis mass flowmeter (CMF). Analog control module is composed of self-oscillation circuit and automatic gain control (AGC), and digital module is designed based on adaptive fuzzy sliding mode controller. Thus, when AGC works in the state of two-phase flow, the intelligent controller plays a role of drive controller to supply the drive coil with the enough voltage. Finally, the proposed approach is verified to be effective with satisfied performance via simulation.**

Keywords-coriolis mass flowmeter; digital-analog drive; adaptive fuzzy sliding mode controller; drive control

I. INTRODUCTION

Coriolis mass flowmeter (CMF) is widely used in petrochemical industry due to its characteristics of large scale, high precision and strong anti-jamming. Its basic principle is to generate and detect Coriolis Effect. Through measure the phase difference between sensor signals, which caused by Coriolis Effect, the mass flow rate proportional to Coriolis force is obtained.

To ensure the normal operation of the flowmeter, the drive system must provide a sinusoidal signal with constant amplitude and stable frequency for the driving coil. In [1-2], automatic gain control (AGC) loop is employed to provide a variable gain, which is multiplied by the amplitude difference to produce a correction voltage, thereby achieving a stable amplitude control. In [3-5], owing to the phase difference between the driving signal and the driving mode vibration signal is , phase locked loop (PLL) is proposed to track natural frequencies in the resonant state. In [6], another frequency control method of self–oscillation is presented. The above methods all belong to the analog control method.

Due to the CMF with analog control scheme is easily effected by ambient temperature and external disturbances, and it has shown poor performance during two-phase flow condition[7-9], Shimada develops a digital-analog drive system in [10], where analog module is used for the startup of the flow tube and digital module is used when the flow tube reaches resonant mode. Based on PI control, Zamora studies an all-digital drive scheme to maintain the resonant mode in the state of two-phase flow in [11]. And Henry investigates a random sequence mode technology for the startup and operation of the flow tube in [12]. Besides, Clarke inserts two nonlinear links into the outer loop of the drive system to improve the quality of the drive signal in [13].

Recent years, nonlinear system control methods have been vigorously developed, such as adaptive control, which could adjust the structure to adapt to the environment[14], variable structure sliding mode control, which is with excellent robustness and is insensitive to interference[15], and fuzzy logic system, which could approximate nonlinear function very well[16-17]. Inspired by the aforementioned discussions, a digital-analog drive system with an adaptive fuzzy sliding mode controller is developed to improve the performance of the Coriolis mass flowmeter.

The rest of this paper is organized as follows. The driving scheme of the Coriolis mass flowmeter is designed in Section 2.The adaptive fuzzy sliding mode control of Coriolis mass flowmeter is given in Section 3. Numerical simulations are conducted to verify the feasibility of proposed approach in Section 4. Conclusions are drawn in Section 5.

II. DRIVING SCHEME OF THE CORIOLIS MASS FLOWMETER

As we all know, CMF has high precision measurement only on the premise that high quality detection unit feedback signal is obtained. And high quality detection unit feedback signal is determined by the vibration of vibration tube. Therefore, efficient, fast and stable drive system is the important guarantee of CMF's accuracy. Ideal drive system provides a periodic force for the vibrating tube, causing the vibrating tube to vibrate periodically at its natural frequency and stable amplitude. However, in practical application, when the fluid is in a state of two-phase flow, damping increases sharply, which results in that AGC couldn't provide enough gain to maintain tubes vibrate. In response to these phenomena, a driving scheme based on intelligent controller is proposed in this paper.

As depicted in Fig.1, the novel driving scheme consists of an analog control module and a digital control module. Analog control module is composed of self-oscillation circuit and AGC, which realizes natural frequency tracking and stable amplitude controlling, respectively. Digital control module includes a signal generator and an intelligent controller, where the signal generator generates a reference signal based on reference amplitude and natural frequency, and the intelligent controller

force the output signal of analog control module to track reference signal.

When AGC works in the state of two-phase flow, the intelligent controller plays a role of drive controller to supply the drive coil with the enough voltage, so that the tubes forced vibration. Thus, compared with analog-driven solutions, this analog-digital hybrid drive solution greatly improves the performance of the CMF.

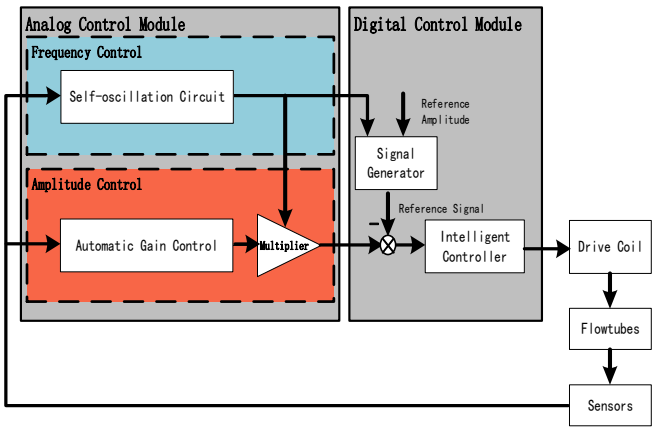

FIGURE I. THE DRIVING SCHEME OF THE CORIOLIS MASS FLOWMETER

III. ADAPTIVE FUZZY SLIDING MODE CONTROL OF CORIOLIS MASS FLOWMETER

A. Model of Coriolis Mass Flowmeter

The model of CMF can be described as a quality-stiffness-damping system, and we have

$$m\ddot{x}+c\dot{x}+kx=f(\mathrm{t}) \tag{1}$$

Where m is the equivalent mass of Coriolis mass flowmeter; x represents the system generalized coordinates; c represents the damping term; k represents the spring term; $f(\mathrm{t})$ is drive force, and $f(\mathrm{t})=ma$, where a is the acceleration.

Both sides of Eq.(1) could be divided by m, so that

$$\ddot{x}+\frac{c}{m}\dot{x}+\frac{k}{m}x=\frac{f(\mathrm{t})}{m} \tag{2}$$

Due to $\omega_n=\sqrt{\frac{k}{m}}$, $\xi=\frac{c}{2m\omega_n}$, Eq.(2) could be expressed as

$$\ddot{x}=-2\xi\omega_n\dot{x}-\omega_n^2x+\frac{f(\mathrm{t})}{m} \tag{3}$$

When $u=\frac{f(\mathrm{t})}{m}$

$$\ddot{x}=-2\xi\omega_n\dot{x}-\omega_n^2x+u \tag{4}$$

Namely,

$$\ddot{x}=A\dot{x}+Bx+u \tag{5}$$

where $A=-2\xi\omega_n$, $B=-\omega_n^2$; u is the input of control strategy

Considering fabrication error, temperature error and external disturbance, Eq.(5) could be indicated as

$$\ddot{x}=(A+\Delta A)\dot{x}+(B+\Delta B)x+u+d(\mathrm{t}) \tag{6}$$

where ΔA, ΔB are parametric uncertainties, including errors caused by manufacturing defect and ambient temperature changes; $d(\mathrm{t})$ is external disturbance, and $|d(\mathrm{t})|\le\eta$.

B. Adaptive Fuzzy Sliding Mode Controller

Define lumped disturbances as $p(\dot{x},x)=\Delta A\dot{x}+\Delta Bx$, according to Eq.(6), we have

$$\ddot{x}=A\dot{x}+Bx+u+p(\dot{x},x)+\mathrm{d}(\mathrm{t}) \tag{7}$$

Where $p(\dot{x},x)$ can be approximated by fuzzy model $\hat{p}(\dot{x},x\,|\,\boldsymbol{\theta})$ and $\hat{p}(\dot{x},x\,|\,\boldsymbol{\theta})$ is composed of N IF-THEN rules. The ith rule has the form

Rule i: IF $\dot{x}_i$ is A_i and x_i is B_i, THEN $\hat{p}(\dot{x},x\,|\,\theta)_i$ is C_i, $i=1,2,\cdots,N$.

Based on singleton fuzzifier, product inference and center average defuzzifier, its output can be expressed as

$$\hat{p}(\dot{x},x\,|\,\boldsymbol{\theta})=\hat{\boldsymbol{\theta}}^T\boldsymbol{\zeta}(\dot{x},x) \tag{8}$$

Where $\zeta(\dot{x},x)_i=\frac{\mu_{A_i}(\dot{x}_i,x_i)\times\mu_{B_i}(\dot{x}_i,x_i)}{\sum_{i=1}^{N}\mu_{A_i}(\dot{x}_i,x_i)\times\mu_{B_i}(\dot{x}_i,x_i)}$ and $\mu_{A_i}(\dot{x}_i,x_i)$, $\mu_{B_i}(\dot{x}_i,x_i)$ are membership function values of the fuzzy variables $\dot{x}_i$, x_i with respect to fuzzy sets A_i, B_i, respectively.

If the fuzzy sets of input variables are defined as $\{N, Z, P\}$, where N is negative, Z is zero, and P is positive, the membership functions of x_i can be selected as

$$\mu_N(x_i)=\begin{cases}1 & x\le-3\\ -\frac{1}{3}x & -3\le x\le 0\end{cases} \tag{9}$$

$$\mu_Z(x_i)=\begin{cases}\frac{1}{3}x+1 & -3\le x\le 0\\ -\frac{1}{3}x+1 & 0\le x\le 3\end{cases} \tag{10}$$

$$\mu_P(x_i)=\begin{cases}1 & x\ge 3\\ \frac{1}{3}x & 0\le x\le 3\end{cases} \tag{11}$$

And the corresponding membership functions of these fuzzy sets labels are shown in Fig.2. As for $\dot{x}_i$, its membership functions are the same with x_i.

The control target for CMF is to maintain the flow tubes oscillate at given frequency and amplitude, such as $x_m = A_m \sin(\omega_x \mathrm{t})$. So, tracking error could be defined as

$$e(\mathrm{t}) = x(\mathrm{t}) - x_m(\mathrm{t}) \tag{12}$$

And sliding mode surface is selected as

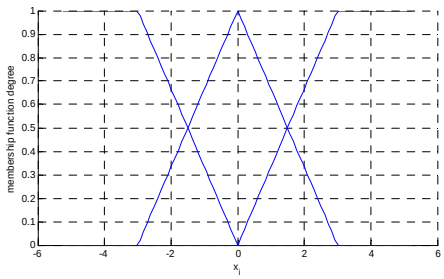

FIGURE II. MEMBERSHIP FUNCTIONS OF x_i

$$s(\mathrm{t}) = \dot{e}(\mathrm{t}) + \beta e(\mathrm{t}) \tag{13}$$

where $\beta > 0$.

So

$$\begin{aligned}\dot{s}(\mathrm{t}) &= \ddot{e}(\mathrm{t}) + \beta\dot{e}(\mathrm{t})\\ &= [\ddot{x}(\mathrm{t}) - \ddot{x}_m(\mathrm{t})] + \beta[\dot{x}(\mathrm{t}) - \dot{x}_m(\mathrm{t})]\\ &= \left[\left(A\dot{x} + Bx + u + p(\dot{x},x) + \mathrm{d}(\mathrm{t})\right) - \ddot{x}_m(\mathrm{t})\right]\\ &\quad + \beta[\dot{x}(\mathrm{t}) - \dot{x}_m(\mathrm{t})]\\ &= (A+\beta)\dot{x} + Bx + u + p(\dot{x},x) + \mathrm{d}(\mathrm{t})\\ &\quad - \ddot{x}_m(\mathrm{t}) - \beta\dot{x}_m(\mathrm{t})\end{aligned} \tag{14}$$

Chose reaching law as $\dot{s}(\mathrm{t}) = 0$, and the controller could be designed as

$$\begin{aligned}u = &-(A+\beta)\dot{x} - Bx - \hat{p}(\dot{x},x|\boldsymbol{\theta}) + \ddot{x}_m + \beta\dot{x}_m\\ &-\eta\,\mathrm{sgn}(\mathrm{s}) - ks\end{aligned} \tag{15}$$

Substituting (15) into (14),

$$\begin{aligned}\dot{s}(\mathrm{t}) &= (A+\beta)\dot{x} + Bx + [-(A+\beta)\dot{x} - Bx\\ &\quad - \hat{p}(\dot{x},x|\boldsymbol{\theta}) + \ddot{x}_m + \beta\dot{x}_m - \eta\,\mathrm{sgn}(\mathrm{s}) - ks]\\ &\quad + p(\dot{x},x) + d(\mathrm{t}) - \ddot{x}_m(\mathrm{t}) - \beta\dot{x}_m(\mathrm{t})\\ &= p(\dot{x},x) - \hat{p}(\dot{x},x|\boldsymbol{\theta}) + d(\mathrm{t}) - \eta\,\mathrm{sgn}(\mathrm{s}) - ks\end{aligned} \tag{16}$$

If the optimal parameters are set as

$$\boldsymbol{\theta}^* = \arg\min_{\substack{\boldsymbol{\theta}\in\boldsymbol{\Omega}\\ \dot{x},x\in R}}\left[\sup\left|\hat{p}(\dot{x},x|\boldsymbol{\theta}) - p(\dot{x},x)\right|\right] \tag{17}$$

Where $\boldsymbol{\Omega}$ is a set of $\boldsymbol{\theta}$.

Then the minimum approximation errors could be defined as

$$w = p(\dot{x},x) - \hat{p}(\dot{x},x|\boldsymbol{\theta}^*) \tag{18}$$

substituting (18) into (16), we have

$$\begin{aligned}\dot{s}(\mathrm{t}) = &\ \hat{p}(\dot{x},x|\boldsymbol{\theta}^*) - \hat{p}(\dot{x},x|\boldsymbol{\theta}) + w\\ &+ d(\mathrm{t}) - \eta\,\mathrm{sgn}(\mathrm{s}) - ks\end{aligned} \tag{19}$$

According to (8), (19) could be expressed as

$$\dot{s} = \boldsymbol{\varphi}^T\boldsymbol{\zeta}(\dot{x},x) + w + d(\mathrm{t}) - \eta\,\mathrm{sgn}(\mathrm{s}) - ks \tag{20}$$

where $\boldsymbol{\varphi} = \boldsymbol{\theta}^* - \boldsymbol{\theta}$.

Select adaptive law as

$$\dot{\boldsymbol{\varphi}} = -rs\boldsymbol{\zeta}(\dot{x},x) \tag{21}$$

Namely,

$$\dot{\boldsymbol{\theta}} = rs\boldsymbol{\zeta}(\dot{x},x) \tag{22}$$

where $\dot{\boldsymbol{\varphi}} = -\dot{\boldsymbol{\theta}}$.

Define Lyapunov function as

$$V = \frac{1}{2}\left(s^2 + \frac{1}{r}\boldsymbol{\varphi}^T\boldsymbol{\varphi}\right) \tag{23}$$

Therefore

$$\begin{aligned}\dot{V} &= s\dot{s} + \frac{1}{r}\boldsymbol{\varphi}^T\dot{\boldsymbol{\varphi}} \\ &= s\left(\boldsymbol{\varphi}^T\boldsymbol{\zeta}(\dot{x},x) + w + d(\mathrm{t}) - \eta\,\mathrm{sgn}(\mathrm{s}) - ks\right) + \frac{1}{r}\boldsymbol{\varphi}^T\dot{\boldsymbol{\varphi}} \\ &= \boldsymbol{\varphi}^T\left(s\boldsymbol{\zeta}(\dot{x},x) + \frac{1}{r}\dot{\boldsymbol{\varphi}}\right) + sw + sd(\mathrm{t}) - \eta|s| - ks^2\end{aligned} \tag{24}$$

Then substituting (21) into (24), we have

$$\dot{V} = sw + sd(\mathrm{t}) - \eta|s| - ks^2 \le sw - ks^2 \tag{25}$$

When fuzzy approximation theory is satisfied, adaptive fuzzy system can approximate nonlinear system closely, so that $\dot{V} \le 0$. And the system is asymptotically stable.

IV. SIMULATION

In this section, numerical simulations are investigated to verify the superiority of novel drive scheme based on intelligent controller, compared with traditional drive scheme.

Parameters of the CMF are as follows:

$\xi = 0.0005$, $\omega_n = 2\pi \times 100 rad/s$.

So set other simulation parameters as

$A = -0.6283$, $B = -394780$, $\beta = 50$, $k = 1000$, $\eta = 2mm$, $r = 0.001$.

Set reference position as

$x_m = A_m \sin(\omega_x \mathrm{t})$ $A_m = 5mm$, $\omega_x = 2\pi \times 100 rad/s$.

And select the initial state values of the system as .

Then the position trajectory is shown in Fig.3, the input of controller is described in Fig.4, and the tracking error is depicted in Fig.5. Obviously within, the tracking error converges to zero.

Through the tracking simulation of flow tube, the proposed approach is with satisfying performance. Therefore, the driving scheme proposed in this paper is feasible.

A. MATLAB Simulation

Starting from 0.2s, the gas content of the fluid increases, which causes damping coefficient increases and natural frequency decreases. Until 0.3s, damping coefficient reaches 0.01, and natural frequency is reduced to 85Hz. At this time, AGC cannot provide enough gain to force vibration tube to vibrate at desired frequency and amplitude.

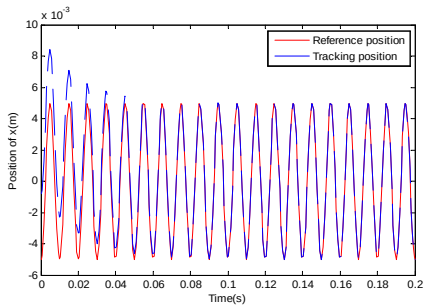

FIGURE III. POSITION TRACKING OF FLOW TUBE

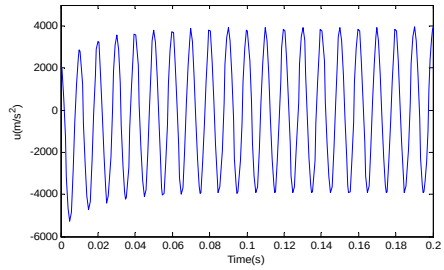

FIGURE IV. INPUT OF ADAPTIVE FUZZY SLIDING MODE CONTROLLER

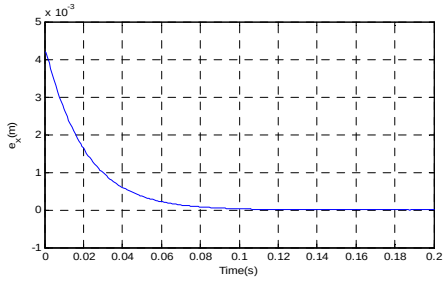

FIGURE V. POSITION TRACKING ERROR OF FLOW TUBE

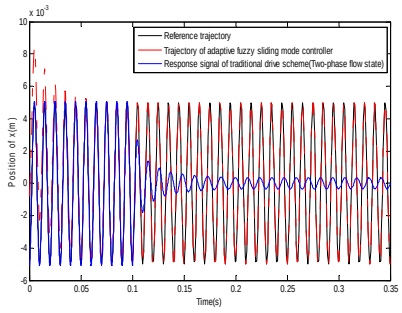

FIGURE VI. DRIVE SIGNALS IN THE STATE OF TWO-PHASE FLOW

As Fig.6 depicts, when the fluid is in the two-phase flow state, the traditional drive program becomes invalid. So, new drive scheme can be used.

B. ANSYS Simulation

As Fig.7 depicts, when the fluid is in the two-phase flow state, amplitude of the traditional drive program becomes smaller and smaller. So, new drive scheme can be used. Fig.8

depicts the novel drive scheme woks well in the state of two-phase flow.

V. CONCLUSION

In this paper, we designed a digital-analog drive scheme based on an adaptive fuzzy sliding mode controller for Coriolis mass flowmeter. On the one hand, when AGC works well, the novel drive scheme could suppress the system uncertainties caused by manufacturing defects, ambient temperature changes and external disturbances. On the other hand, when AGC works in the state of two-phase flow, adaptive fuzzy sliding mode controller plays a role of drive controller to supply the drive coil with the enough voltage. Therefore, the performance of drive program for Coriolis mass flowmeter is improved. Finally, simulation results are presented to demonstrate the effectiveness of the design.

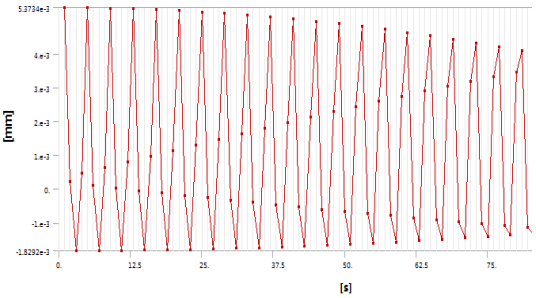

FIGURE VII. RESPONSE SIGNAL OF TRADITIONAL DRIVE

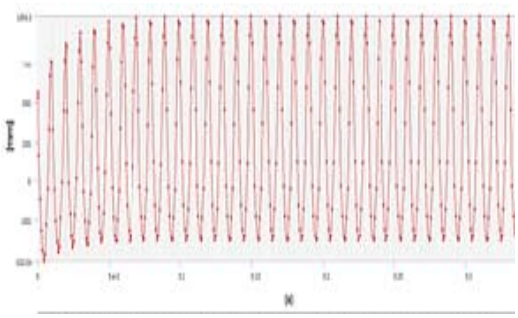

FIGURE VIII. TRAJCTORY OF ADAPITIVE FUZZY SLIDING MODE CONTROLLER

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China under Grant 60974109.

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