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Electromagnetic Flow Detection Technology Based on Correlation Theory

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ABSTRACT When the electromagnetic flowmeter (EMF) is applied to the industrial field, the effective flow signal of the electrode output is easily drowned out by the noise under the condition of strong noise and flow rate lower than 0.2 m/s. However the flow signal drowned out in strong noise cannot be measured accurately by traditional electromagnetic flow detection technology, which cannot separate signal and noise effectively. The correlation technology can be applied to select the reference signal with the same regularity as the target signal to separate the target signal and remove the noise. Firstly, researches on the correlation detection and the basic correlation theory of the electromagnetic flowmeter are carried out. Then, the design of the electromagnetic flow measurement system based on the theoretical research is completed. Finally, in order to verify the performance and accuracy of the designed flow measurement system, a test platform for electromagnetic flow detection is set up, and the verification experiments are implemented. The experiment results show that the electromagnetic flow measurement system based on the correlation theory can not only meet the requirements of traditional flow measurement but also have unique advantages in suppression of strong noise interference, slurry flow measurement, and low flow rate measurement.

INDEX TERMS Correlation detection, electromagnetic flow measurement, interference suppression, lock-in amplification, weak signal detection.

I. INTRODUCTION

The electromagnetic flowmeter, an instrument to measure liquid flow, developed rapidly in the 1960s with the improvement of electronic technology [1]. The output flow signal of electromagnetic flowmeter electrodes is very weak and mixed with many kinds of interference simultaneously. The main interference signals include differential interference, in-phase interference, power-line interference, serial mode interference, common mode interference and electrochemistry interference [2]–[7]. These interference must be suppressed and eliminated in order to obtain stable flow signals. The anti-interference technologies to improve the flow measurement performances of EMF mainly include new excitation technology, prefilter amplification, simultaneous sampling frequency compensation, and data acquisition etc [8]–[10]. A. B. Denison et al proposed the low frequency excitation in 1956 [11]. Low frequency excitation, with excellent anti-interference performance, is easily used for flow signal processing, and therefore widely applied in electromagnetic flowmeters. Although the performance of the electromagnetic flowmeter has been continuously improved with the progress of the theoretical study, the eddy current effect, quadrature interference and in-phase interference have still remained in traditional flow measurement. Yokogawa Electrical and Mechanical Company in Japan, developed an

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excitation method of high and low frequency-modulated rectangular waves, namely double-frequency rectangular excitation technology in 1988 [12], based on the characteristics of various excitation methods. With this technology, the zero-point stability and the ability to suppress mud interference and flow noises of the low frequency rectangular wave excitation were improved. Moreover, it further reduced the excitation power consumption and improved the signal-to-noise ratio (SNR) of the output signal of the electromagnetic flow sensor, making it the most advanced excitation technology in the field of electromagnetic flowmeter [13]. T.Zhang analyzed the influence of different excitation frequencies, the number of sampling points and sampling width on the measurement accuracy, and improved measurement accuracy and measurement range based on the result of theoretical analysis. However, this method mainly worked on eliminating power-line interference under low flow rate or low excitation current conditions [14]. According to the distribution characteristics of the series mode interference frequency and the measured signal frequency, the researchers applied the appropriate filters (such as active RC filtering circuit or passive low pass filter) to remove the series mode interference effectively [15]. Y.D.Xiao et al analyzed the impact of working processes of these filters on their performance, and designed the lock-in amplifier with a filter to remove the noise effectively. These researchers also carried out some experiments to prove that the pre-filter can greatly reduce the output noise of the system and increase the SNR [16]. J.Z.Wang et al proposed a new finite element method to solve the weight function of electromagnetic flowmeter. It can reduce the influence of magnetic field interference when the fluid contains a certain proportion of solid particles [17].

All these methods only work on the elimination of a single kind of interference. However, effectively removing all kinds of interference in the output signal of the electromagnetic flowmeter, and extracting the flow signal, are key to improving the measurement accuracy of the electromagnetic flowmeter. In recent years, the lock-in amplification technology has been widely applied to all aspects of scientific research. Lock-in amplification technology can extract weak flow signals from an environment full of strong noises with its unique and simple signal processing method. It can be widely used in the measurement of contact resistance, optical fiber sensing, and the detection of weak signal such as laser signal [17]. Moreover, it is also applied in laser distance measuring, infrared spectrum analysis, nondestructive testing, and strain measurement etc. With the progress of technology, the lock-in amplification performance will be further improved and have a profound impact on the measurement technology. J.Guan first explored the signal detection technology of the electromagnetic flowmeter by using the correlation principle, and proposed new ideas for the development of the electromagnetic flowmeter based on the correlation detection principle [18]. However, he only proposed the concept of correlation principle applied in the field of electromagnetic flowmeter, without carrying researches in depth. Our paper proposes a method to extract the flow signal under the condition of strong external interference, high solid particle content and flow rate lower than 0.2m/s. The method is based on the combination of lock-in amplification and traditional weak signal amplification. It is worth emphasizing that there has not been any literature introducing the electromagnetic flow measurement system based on the correlation detection principle. Moreover, this system not only meets the requirements of traditional flow measurement but also has unique advantages in strong noise interference suppression, slurry flow measurement, and low flow rate measurement.

The remainder of this paper is organized as follows. Section 2 introduces the correlation detection model of electromagnetic flowmeter. Section 3 describes the system design and experiment work. Section 4 contains the results of the data analysis. Section 5 contains our conclusions.

II. CORRELATION DETECTION MODEL OF ELECTROMAGNETIC FLOWMETER

A. OUTPUT SIGNAL MODELLING OF ELECTROMAGNETIC FLOWMETER

As for an electromagnetic flowmeter with low frequency rectangular wave excitation, the voltage obtained from the electrodes contains not only an induction electromotive force that is proportional to the flow rate, but also a variety of interference components, including power-line interference, differential interference, common mode interference, series mode interference and electro-chemical interference [19]. The voltage signals on the electrodes of the electromagnetic flowmeter can be expressed in equation (1).

$$E = BvD + \mathrm{k}_1\frac{dB}{dt} + k_2\frac{d^2B}{dt^2} + e_c + e_d + e_z \tag{1}$$

where BvD is the measured flow signal obtained by the electromagnetic flowmeter; $k_1\frac{dB}{dt}$ is differential interference, which is caused by the induction electromotive force generated in the closed loop during the sudden change of magnetic field; $\mathrm{k}_2\frac{d^2B}{dt^2}$ is in-phase interference, which increases when the differential interference gets larger; e_c is common mode interference, which is caused by electrostatic interference and electromagnetic interference; e_d is series mode interference; e_z is electrochemical interference, which mainly includes slurry interference, polarization interference and flow noise. The waveform of the output signal of the electromagnetic flowmeter is shown in Figure 1.

Differential interference and in-phase interference are the main interference types of electromagnetic flowmeters. The traditional noise elimination method mainly works on removing differential interference and in-phase interference. However, when the magnetic field is stable, differential interference and in-phase interference will disappear automatically. The stable stages can be extracted by sampling and holding, but common mode interference, series mode interference and electrochemical interference are not negligible [13]–[15]. Firstly, the series mode interference mixed into effective signals is difficult to separate. It saturates the

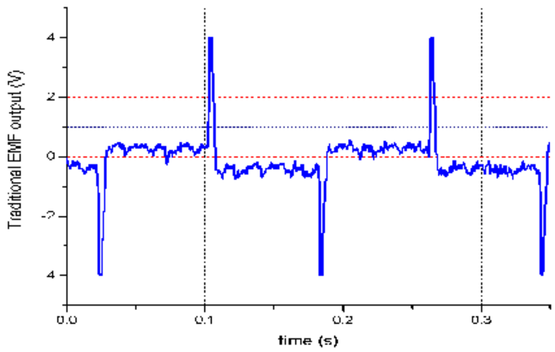


FIGURE 1. Output signal of electromagnetic flowmeter with interference signals.

measurement amplifier easily, weakens the linearity of the signal, and influences the zero-point stability of the electromagnetic flow signal greatly. Then, the common mode interference does not directly affect the measurement results, but it can be transformed to series mode interference which affects the measurement results when the input parameters of the switching amplifier are asymmetric. Finally, due to slurry interference, the output signal of electromagnetic flowmeters in the slurry flow measurement contains randomly generated large jump noise with the spectrum distribution of $1/f$, and can hardly be removed by traditional signal processing. These interferences often affect the accuracy of measurement even leading to the failure to carry out the measurement. Therefore, effectively removing these three kinds of interferences is the key to improving measurement accuracy. According to Faraday's law, the frequency of effective signal (BvD) in the electrode output of the electromagnetic flowmeter should be the same as the frequency of the excitation signal. The low frequency rectangular wave excitation is applied in the electromagnetic flowmeter studied in this paper. Therefore, if the rectangular wave with the same frequency as the excitation wave is used as the reference signal, correlation detection technology can be used to remove the noise (including common mode interference, series mode interference and electrochemical interference) in the output signal of the electrodes effectively. If the traditional method [23] and correlation detection technology work together, complex situations of strong external interference, high solid particle content, and flow rate below 0.2m/s, can be treated more effectively.

B. DETECTION MODEL BASED ON CORRELTATION PRINCIPLE

Since the low frequency rectangular wave excitation is applied in the electromagnetic flowmeter based on correlation principle, the measured flow signal can be idealized as the rectangular signal. According to Faraday's law, the frequency and phase of the excitation signal are almost identical to those of the measured signal [24]. Hence, in this system the rectangular excitation wave is used as the reference signal, which can be expressed by the symmetric square wave function with unit amplitude.

The schematic diagram of the electromagnetic flowmeter based on correlation theory is shown in Figure 2. Assuming that the flow signal with noise V_f and excitation reference signal V_{ex} are multiplied in a multiplier, V_I is not only the output signal of the multiplier, but also the input signal of the integrator. The resistances R_0, R_1, and capacitance C_0 of the integrator, are shown in Figure 2. V_0 is the output signal of the integrator and also the correlation function of the correlator output. The multiplication of the flow signal and the excitation reference signal with unit amplitude can be operated in the switch multiplier. The excitation reference signal can be expressed in equation (2).

$$V_{ex} = \frac{4}{\pi}\sum_{n=0}^{\infty}\frac{1}{2n+1} sin(2n+1)\cdot \omega f \cdot t \tag{2}$$

where ω_f is the angular frequency of the excitation reference signal, n a natural number and t the integration time. The flow signal with noise can be expressed as:

$$\mathrm{S}V_f = \frac{4}{\pi}V_{am}\sum_{n\to 0}^{\infty}\frac{1}{2n+1}\sin(2n+1)\cdot\omega_R(t+\tau)+n(t) \tag{3}$$

where ω_{R} is the angular frequency of the signal; τ is the delay time of the input signal relative to the excitation reference signal; V_{am} is the amplitude of the rectangular wave of the flow detection signal; n(t) is the noise interference in electrode output signal of electromagnetic flowmeter. The integrator input voltage V_I and the output voltage V_0 satisfy the differential equation (4).

$$C_0\frac{dV_0}{dt} + \frac{V_0}{R_0} = -\frac{V_I}{R_1} \tag{4}$$

By simplifying equation (4), we have:

$$\frac{dV_0}{dt} + \frac{1}{R_0C_0}V_0 = -\frac{V_I}{C_0R_1} \tag{5}$$

Equation (5) is a first-order linear differential equation, and the general solution is shown in equation (6):

$$V_0 = exp\left(-\int_0^t\frac{dt}{R_0C_0}\right)\left[\int_0^t\left(-\frac{V_I}{R_1C_0}\right)\cdot exp\left(\int_0^t\frac{dt}{R_0C_0}\right)dt + C\right] \tag{6}$$

where C is an undetermined constant; the initial voltage of C_0 is 0.

$$\begin{aligned} V_I &= V_f \cdot V_{ex} \\ &= [\frac{4}{\pi}V_{am}\sum_{n=0}^{\infty}\frac{1}{2n+1}\sin(2n+1)\omega_R(t+\tau)+n(t)] \\ &\quad \times\frac{4}{\pi}\sum_{2n+1}^{1}\sin(2n+1)\omega_R t \\ &= \frac{4}{\pi}V_{am}\sum_{n=0}^{\infty}\frac{1}{2n+1}\sin(2n+1)\cdot\omega_R(t+\tau) \end{aligned}$$

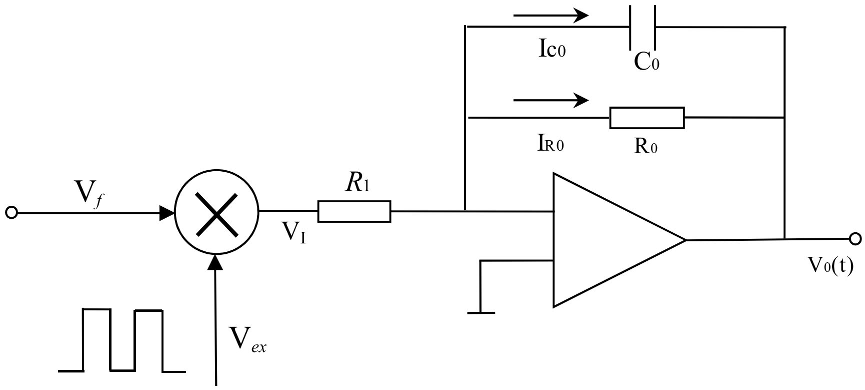


FIGURE 2. Correlation detection principle of the electromagnetic flowmeter.

$$\times \frac{4}{\pi}\sum_{2n+1}^{1}\sin(2n+1)\omega_R t$$
$$+n(t)\cdot\frac{4}{\pi}\sum_{2n+1}^{1}\sin(2n+1)\cdot\omega_R t \quad (7)$$

The product of noise n(t) and excitation reference signal is:

$$n(\mathrm{t})\cdot\frac{4}{\pi}\sum_{n=0}^{\infty}\frac{1}{2n+1}\sin(2n+1)\cdot\omega_R t \quad (8)$$

To make the following deduction easier, suppose the noise $n(t) = V_N \sin\omega_N t$, and substitute it into formula (8):

$$V_N\sin\omega_N t\cdot\frac{4}{\pi}\sum_{n=0}^{\infty}\frac{1}{2n+1}\sin(2n+1)\omega_R t \quad (9)$$

where V_N is the amplitude of noise, ω_n is the noise frequency (the superposition of noise frequency and flow signal frequency in electromagnetic flowmeter can be neglected).

According to the research on cross-correlation detection methods [19], when the integration time is long enough, and the excitation reference frequency is the same as the frequency of the electromagnetic flow signal, the cross-correlation between the noise n(t) and the excitation reference signal is 0. So only $\frac{4}{\pi}V_{am}\sum_{n=0}^{\infty}\frac{1}{2n+1}\sin(2n+1)\omega_R(t+\tau)$ and excitation reference signal are correlated.

By substituting the product of the excitation reference signal V_{ex} and the first item in the expression of flow signal V_f into equation (6), we have:

$$V_0 = -\frac{8V_{am}R_0}{\pi^2 R_1}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\left\{\left(\cos(2n+1)\omega_R\tau-\frac{\cos(2n+1)\omega_R\tau\cos[2(2n+1)\omega_R t-\theta_1]}{\sqrt{1+[2(2n+1)\omega_R\tau_0]^2}}\right.\right.$$
$$-\frac{\sin(2n+1)\omega_R\tau\cos[2(2n+1)\omega_R t-\theta_2]}{\sqrt{1+[2(2n+1)\omega_R\tau_0]^2}}$$
$$-\left(\cos(2n+1)\omega_R\tau-\frac{\cos(2n+1)\omega_R\tau\cos\theta_1}{\sqrt{1+[2(2n+1)\omega_R\tau_0]^2}}\right.$$
$$\left.\left.-\frac{\sin(2n+1)\omega_R\tau\cos\theta_2}{\sqrt{1+[2(2n+1)\omega_R\tau_0]^2}}\right]\exp\left(-\frac{t}{\tau_0}\right)\right\} \quad (10)$$

where $\theta_2 = arctg\frac{1}{2(2n+1)\omega_R R_0 C_0}$, $\tau_0 = R_0C_0 = T_C$, and $\theta_1 = arctg2(2n+1)\omega_R R_0 C_0$.

When $\omega_R R_0 C_0 \gg 1$, equation (10) can be simplified, as shown in equation (11):

$$V_0 = -\frac{8R_0V_{am}}{\pi^2 R_1}\left[1-\exp\left(-\frac{t}{R_0C_0}\right)\right]\times\sum_{0}^{\infty}\frac{1}{(2n+1)^2}\cos(2n+1)\omega_R\tau \quad (11)$$

According to the infinite progression equation,

$$y=\frac{C}{2}-\frac{4C}{\pi^2}\left[cos\frac{\pi y}{C}+\frac{1}{3^2}cos\frac{3\pi y}{C}+\frac{1}{5^2}cos\frac{5\pi y}{C}+\ldots\ldots\right] \quad (0<y<C) \quad (12)$$

where C is any constant.

Substitute $y = \frac{C\omega_R\tau}{\pi}$ into the equation above:

$$\frac{4}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\cdot cos(2n+1)\omega_R\tau = \frac{1}{2}-\frac{\omega_R\tau}{\pi} \quad (13)$$

Then substitute equation (13) into equation (11):

$$V_0 = -\frac{R_0V_{am}}{R_1}\left[1-exp\left(-\frac{t}{R_0C_0}\right)\right]\left[1-\frac{2\omega_R\tau}{\pi}\right] \quad (14)$$

When $t \gg T_C = R_0C_0$, and $\varphi = \omega_R\tau$, the equation (14) can be written as :

$$V_0 = -\frac{R_0V_{am}}{R_1}\left(1-\frac{2\varphi}{\pi}\right) \quad (15)$$

Based on the deduction above, the following conclusions can be obtained:

1) When there is interference signal in the output signal, the result of correlation between the output signal and the excitation reference signal is the cross-correlation

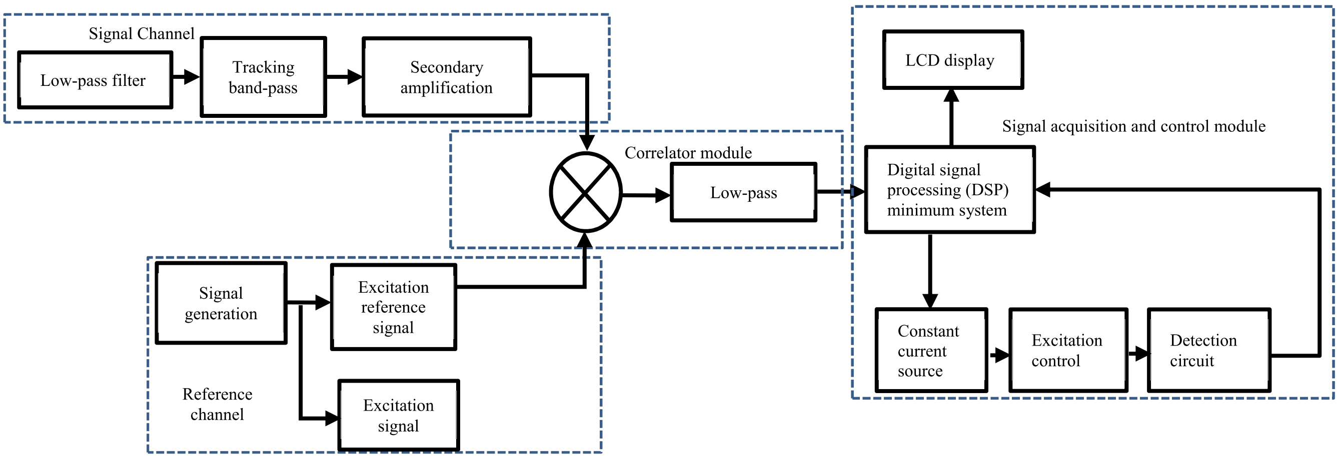


FIGURE 3. Self-made electromagnetic flowmeter hardware structure.

function between the flow signal and the reference signal, which is independent of the interference signal amplitude.

2) In the system, the output DC voltage signal is the product of flow signal amplitude V_{am} and DC amplification $\frac{R_0}{R_1}$, and is linearly related to the phase difference φ between the two rectangular waves.

3) When the phase difference between the electrode output signal and the excitation reference signal is zero constantly and the amplification $\frac{R_0}{R_1}$ is determined, the amplitude of the electromagnetic flow signal V_{am} is directly related to the output voltage of lock-in amplifier.

III. SYSTEM DESIGN AND EXPERIMENTAL WORK

After setting up the whole measurement system, it is necessary to test the function of each module and the whole system to verify the feasibility and rationality of the system design. The hardware structure of self-made electromagnetic flowmeter is shown in Figure 3.

A. SYSTEM REALIZATION OF ELECTROMAGNETIC FLOWMETER BASED ON CORRELATION PRINCIPLE

The signal processing circuit designed in this paper is based on the electromagnetic flowmeter with the low frequency rectangular wave as the excitation signal, including a reference signal channel processing circuit, a signal conditioning circuit and a correlator circuit [25]. The self-made electromagnetic flowmeter is shown in Figure 4.

1) REFERENCE CHANNEL

According to the principle of lock-in amplification, it is feasible to use the excitation signal as the reference signal of a lock-in amplifier. The excitation signal can be generated by direct digital frequency synthesis (DDS) technology [26].

2) SIGNAL CHANNEL

In order to suppress the common mode interference of the system as much as possible, a differential electrode structure

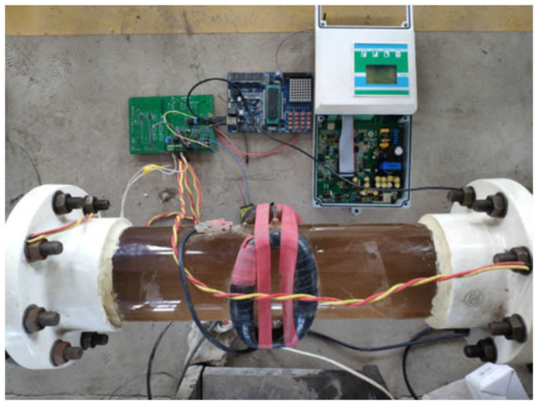


FIGURE 4. Self-made EMF.

is used in the output of the electromagnetic flow sensor, and this electrode structure is composed of positive, negative and ground electrodes. In order to ensure that the signal is not distorted, the gain of the preamplifier circuit must be set within 10, so the voltage of the output signal was still very small, which needed to be amplified again. Two-stage amplification was used to meet the requirements of the subsequent circuit.

After being processed by the preamplifier, the flow signal may still be mixed with high-frequency spike noise and small DC components in the output signal of the sensor. These interference need to be removed by a band-pass filter. In practical applications, different excitation frequencies should be applied to improve the accuracy of flow measurement according to the different properties of the fluid. The filtering method can be optimized in the system and the automatic tracking frequency filtering technology can be successfully realized [27], [28].

3) CORRELATOR MODULE

In both correlation function and correlation detection, there are multiplications of two functions. In the circuit, a phase

FIGURE 5. Experimental platform.

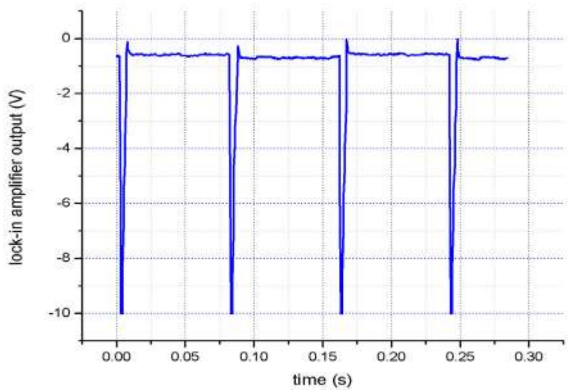


FIGURE 6. Output signal processed by the lock-in amplifier.

sensitive detector or a mixer, an important part of correlation detection technology, is usually used to implement the multiplication, and the output signal frequency can be transformed from ω_0 to $2\omega_0$. If the input signal and the reference signal have different frequencies, the output will be in the spectrum range of $2\omega_0$ and thus be filtered by the low-pass filter. On the other hand, when the input signal and the reference signal have the same frequency, $\Delta\omega_0 = 0$. Thus, the DC signal only related to the sizes and the initial phases of the two signals can be obtained [29]–[31].

4) SIGNAL ACQUISITION AND CONTROL MODULE

This module is composed of constant current source, excitation control, detection circuit, DSP, and LCD display, and is mainly used to realize excitation signal control, excitation current detection, as well as acquisition, processing, analysis and display of the flow signal. The reference signal is the square wave generated by the PWM module of the DSPF28335, and the frequency is 6.25Hz.

B. EXPERIMENT SETUP AND DESIGN

In order to verify the performance of the electromagnetic flowmeter based on correlation principle, an experimental platform was designed and constructed. As shown in Figure 5, this experiment took Yokogawa ADMAG AXW electromagnetic flowmeter with accuracy level of 0.5 as the standard meter. This flowmeter can measure low flow rate and calibrate the self-made electromagnetic flowmeter based on correlation principle. The traditional electromagnetic flowmeter is used as a comparator to evaluate the performance of self-made electromagnetic flowmeter. The frequency can be adjusted by automatically controlling the frequency converter, thus the flow rate can be changed.

In this experiment, the flow rates ranged from 0.141m/s to 2.00 m/s. Data at 14 different flow rates were taken by comparing the standard electromagnetic flowmeter reading with the readings of the self-made electromagnetic flowmeter and traditional electromagnetic flowmeter. The average value was then calculated. Self-made electromagnetic flowmeter was tested under the conditions of strong interference, solid particles and low flow rate in order to verify the superiority of the electromagnetic flow detection technology based on the correlation principle.

IV. RESULTS AND ANALYSIS

The structure of this section is organized as follows. Firstly, the response characteristics of the correlation electromagnetic flowmeter are described; then, the calibration result is shown and analyzed; finally, data obtained from the tests under special conditions, including external strong interference, slurry fluid and low flow rate, are presented and analyzed.

A. RESPONSE CHARACTERISTICS OF ELECTROMAGNETIC FLOWMETER BASED ON CORRELATION PRINCIPLE

With the flow signal as input and the excitation signal as the reference signal, there was a phase difference of 180 degrees between the reference signal and the measured signal. After the multiplication operation by the phase sensitive detector, the processed signal was input into the low pass filter and the DC signal was obtained. The waveform after being processed by the phase sensitive detection is shown in figure 6.

It can be found that the waveform after being processed by the lock-in amplifier actually overturns downward the original waveform with the zero point as the symmetry axis. The phase difference between the reference signal and flow signal is 180 degrees. After being processed by the low pass filter, the waveform is approximately a straight line, which is consistent with the previous theoretical study [32].

B. CALIBRATION RESULTS

The frequency change of the transducer led to the variation of the flow rate, and flow rate variation caused the difference of the output effective voltage of the low pass filter. The data acquisition system was used to collect the DC voltage of the output of the lock-in amplifier, and the flow rate of the standard flowmeter was recorded, as shown in Table 1.

According to the calculation, the linearity between the output voltage of self-made electromagnetic flowmeter and

TABLE 1. Data of flow rate measurement.

Frequency (Hz)	Standard flowmeter (m/s)			Output of self-made electromagnetic flowmeter (mV)		
	min	max	avg	min	max	avg
3	0.140	0.141	0.141	132	135	134
5	0.239	0.240	0.240	84.0	88.0	86.0
7	0.331	0.332	0.332	43.0	47.0	45.0
9	0.426	0.427	0.427	4.00	5.00	4.50
11	0.522	0.523	0.523	-41.0	-38.0	-39.5
13	0.618	0.619	0.619	-85.0	-81.0	-83.0
15	0.724	0.725	0.725	-134	-129	-132
17	0.823	0.824	0.824	-175	-173	-174
19	0.926	0.927	0.927	-224	-222	-223
20	0.974	0.975	0.975	-248	-245	-247
25	1.24	1.24	1.24	-364	-360	-362
30	1.49	1.50	1.50	-474	-470	-472
35	1.75	1.75	1.75	-586	-583	-585
40	2.00	2.00	2.00	-709	-706	-708

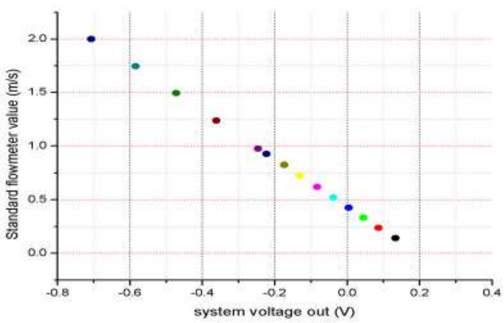


FIGURE 7. The relationship between the output value and the flow rate of the self-made electromagnetic flowmeter.

the flow rate is shown in equation (16):

$$y = -2.2294x + 0.4431 \tag{16}$$

where y is the flow rate and x is the output voltage of the self-made electromagnetic flowmeter. The coefficients a = −2.2294, b = 0.4431 in equation (16) are the instrument coefficients of the tested flowmeter. It can be found that the flow change can be linearly expressed by the output voltage of the tested flowmeter, and the linearity between the flow change and output voltage is excellent. As shown in Figure 7, R squared, as the extent index of the trend linear fitting of the straight line, is equal to 0.9999. The extent index is important to describe the static characteristics of the sensor. A high extent index shows a better linear feature and a higher stability of the system.

After a calibration test, the meter factors were input into the self-made electromagnetic flowmeter, and an instantaneous flow can be obtained directly. In this test, six test points were chosen, and four tests were conducted at each point. The test results are listed in Table 2.

TABLE 2. Test results of self-made electromagnetic flowmeter.

Test points (converter frequency ,Hz)	Standard EMF (instantaneous flow,m^3/h)	Self-made EMF (instantaneous flow,m^3/h)	Flow difference(m^3/h)	Relative indication error(%)	Mean error(%)
40.0	56.5	56.5	-0.0280	-0.0500	0.283
	56.5	56.7	0.226	0.400	
	56.5	56.8	0.283	0.500	
30.0	42.2	42.1	-0.113	-0.268	-0.223
	42.3	42.0	-0.226	-0.535	
	42.2	42.3	0.0570	0.134	
20.0	27.5	27.4	-0.141	-0.513	0.0680
	27.6	27.7	0.113	0.410	
	27.6	27.7	0.0850	0.307	
11.0	14.8	14.8	0.0570	0.382	0.193
	14.8	14.6	-0.113	-0.766	
	14.7	14.8	0.141	0.962	

According to Table 2, the maximum relative indication error in a single test is −0.766%, and the minimum one is −0.050%. Besides, the maximum average relative indication error is 0.283%, and the minimum average relative indication error is 0.068%. By comparison with the relative indication error, the average relative indication error at each test point is much smaller. The relative indication error of each test point can be reduced after being averaged. At present, the measurement error of commonly used high-precision electromagnetic flowmeter is 0.5%, so the accuracy of self-made electromagnetic flowmeter is better than that of commonly used high-precision electromagnetic flowmeter.

C. TESTS UNDER SPECIAL CONDITIONS

1) TEST UNDER THE CONDITION OF EXTERNAL STRONG INTERFERENCE

In the experiment, an electric drier was used to introduce synchronous periodic impulse noises into the system, to test fluctuation rate of the output value of the system. The test was conducted at 24Hz.

According to Figure 8, the waveform of the traditional electromagnetic flowmeter shown in Figure 1 is affected by external strong interference. The wave fluctuates between 0-0.500V, which influences the calculation of the voltage difference and thus the accuracy of the flow rate measurement. However, the designed system based on the correlation principle can suppress the external interference well, making the output stable. The output value is only 15mV, making calculations easier and helping to improve the accuracy of the measurements.

2) SLURRY FLUID TEST

The bentonite of a certain ratio (3‰) was added into the liquid storage tank. The data acquisition commenced when the

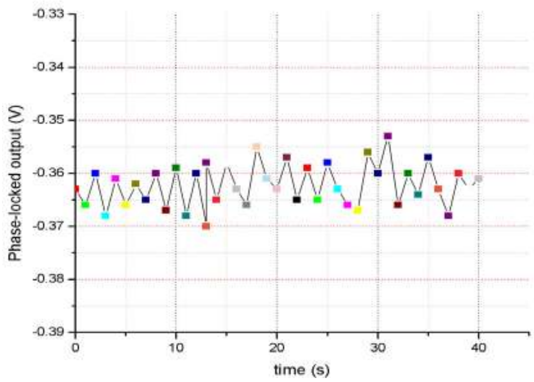


FIGURE 8. Output signal in strong noises at 24Hz.

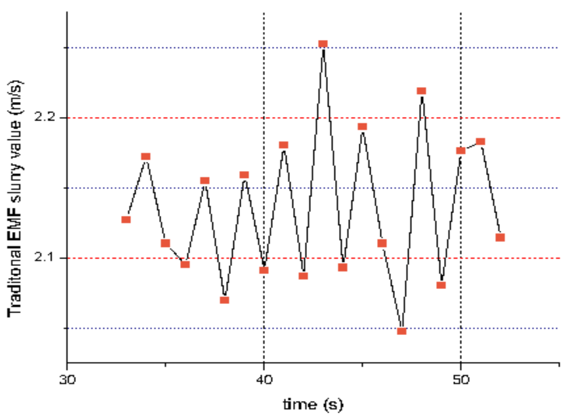


FIGURE 9. Traditional electromagnetic flowmeter slurry output.

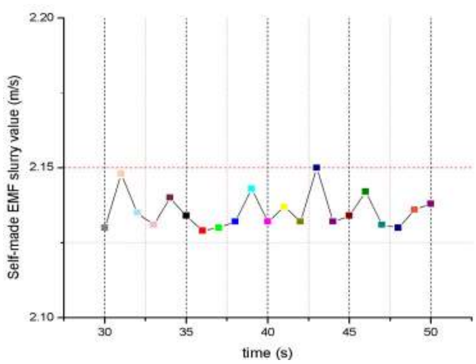
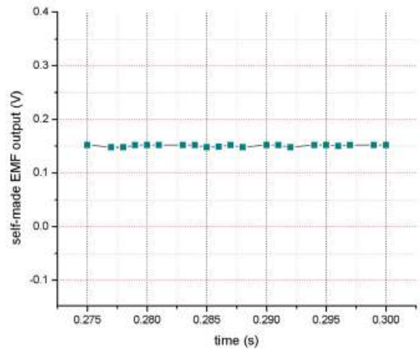


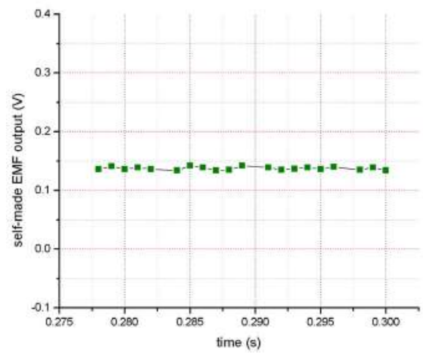
FIGURE 10. Self-made electromagnetic flowmeter slurry output.

bentonite was mixed fully and distributed homogeneously, as shown in Figure 9.

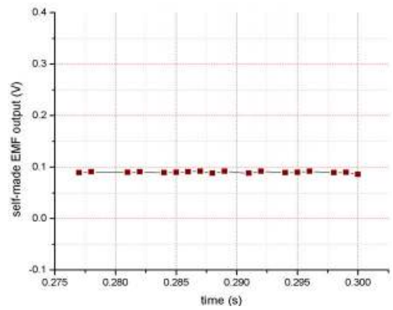
Figure 9 shows that the slurry measurement of the traditional electromagnetic flowmeter is obviously affected by slurry interference, and the flow rate fluctuated between 2.050∼2.250 (m/s). Figure 10 shows that self-made electromagnetic flowmeter can effectively remove the slurry interference. The flow rate fluctuates between 2.130 m/s and 2.150 m/s, and the fluctuation range is apparently less than that of the traditional electromagnetic flowmeter. Hence, the self-made electromagnetic flowmeter works better on suppressing the slurry interference and improving the measurement accuracy.



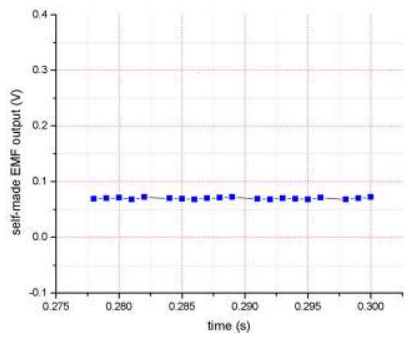
(a) Output signal of self-made electromagnetic flowmeter when the standard meter flow rate is 0m/s



(b) Output signal of self-made electromagnetic flowmeter when the standard meter flow rate is 0.142m/s



(c) Output signal of self-made electromagnetic flowmeter when the standard meter flow rate is 0.196m/s



(d) Output signal of self-made electromagnetic flowmeter when the standard meter flow rate is 0.224m/s

FIGURE 11. Output signal of low flow rate test.

3) LOW FLOW VELOCITY TEST

The frequency of the transducer increased from 0 Hz and the flow rates of the standard flowmeter were recorded at

TABLE 3. Low flow rate test data.

Frequency(Hz)	Standard flowmeter (m/s)			The output of self-made electromagnetic flowmeter (mV)		
	min	max	avg	min	max	avg
2.00	0.099	0.101	0.100	165	167	166
2.10	0.102	0.103	0.103	159	160	160
2.20	0.106	0.107	0.107	157	159	158
2.30	0.113	0.114	0.114	154	157	156
2.40	0.117	0.118	0.118	152	153	153
2.50	0.122	0.123	0.123	148	150	149
2.60	0.126	0.127	0.127	143	147	145
2.70	0.130	0.131	0.130	140	144	142
2.80	0.134	0.136	0.135	138	140	139
2.90	0.135	0.136	0.136	134	137	136
3.00	0.140	0.141	0.140	132	135	134

the frequencies of 3.5Hz, 4.5Hz and 5.5Hz respectively. The output waveform of self-made electromagnetic flowmeter was recorded, as shown in Figure 11.

According to Figure 11, with the increasing of flow rate, the output voltage of self made EMF decreases apparently. It can be found qualitatively that this self-made electromagnetic flowmeter responds to different flow rates sensitively in the low flow rate test. Then, its ability to detect the low flow rate was analyzed quantitatively. The frequency of the transducer increased from 2Hz, with a step of 0.10Hz.

The flow rate shown by the standard flowmeter, as well as the corresponding maximum and minimum output of the self-made electromagnetic flowmeter was recorded, as shown in Table 3.

According to Figure 12, it can be found that under low flow rate condition, the output of the self-made electromagnetic flowmeter has a good linearity with the output of standard flowmeter (when the square of R is 0.977), and the slope of the curve is nearly the same as that in Figure 7. The output signal of the self-made electromagnetic flowmeter is a DC signal, but it still has signal jitter because there is a spike in the measured flow rate signal and the amplitude of the spike is relatively large. Though the correlator, with an integrator, can still filter the waves, the capacitance in the integrator cannot be set too high in order to satisfy the requirements for the response to the flow signal. Therefore, the output signal of electromagnetic flowmeter based on correlation principle also have periodic fluctuations.

To verify the advantages of the system proposed above over the traditional electromagnetic flowmeter on the measurement accuracy, the low flow rate experiments on this system and traditional electromagnetic flowmeter were carried out under the same experimental conditions, and the data was obtained, as shown in Table 4.

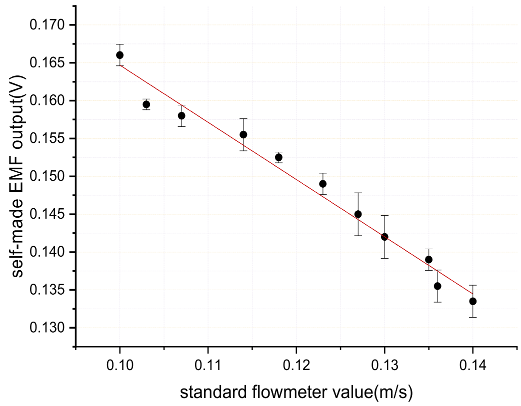


FIGURE 12. Low flow rate test.

TABLE 4. Comparison of measurement results between flow measurement system based on correlation theory and traditional flowmeter.

Standard flowmeter (m/s)	Traditional electromagnetic flowmeter (m/s)	Self-made electromagnetic flowmeter (m/s)	Relative error between High-precision EMF and self-made EMF (%)	Relative error between High-precision EMF and traditional EMF(%)
0.100	0.0790	0.0980	-2.00	-21.0
0.114	0.0940	0.112	-1.80	-17.5
0.123	0.104	0.120	-2.40	-15.4
0.139	0.111	0.129	-0.800	-14.6
0.135	0.116	0.133	-1.50	-14.1
0.140	0.122	0.140	0.00	-12.9

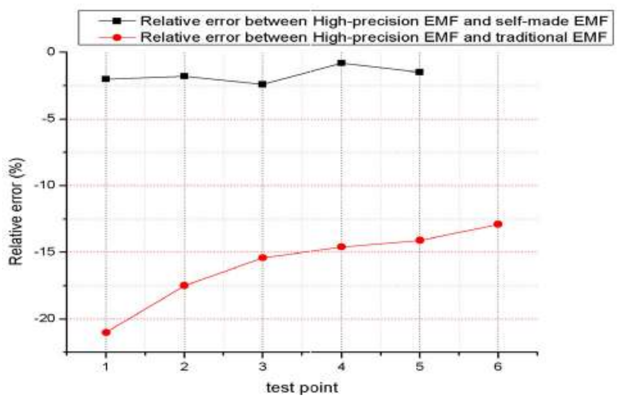


FIGURE 13. Comparison of error distributions.

To compare the performances of traditional electromagnetic flowmeter and the one based on correlation principle, Figure 13 can be drawn according to Table 4. Under the condition of low flow rate, the maximum error of this system is only -2.4%, and the maximum relative error of traditional electromagnetic flowmeter is -21.0%. Obviously, under the same conditions, the measurement accuracy of the flow measurement system based on correlation principle is much higher than that of the traditional electromagnetic flowmeter.

V. CONCLUSION

This paper proposed an electromagnetic flow measurement system based on the correlation detection principle. The following conclusions can be drawn according to the analysis and tests mentioned above:

1) In the study of the correlation theory of electromagnetic flow measurement, a theoretical model of the electromagnetic flow-measurement based on correlation principle was created, and the electromagnetic flowmeter based on this model was designed.

2) The self-made electromagnetic flowmeter based on correlation principle and the measurement system were designed, and verification experiments were carried out. The results of these experiments showed that the electromagnetic flow measurement system based on the correlation principle can not only meet the requirements of traditional flow measurement, but also have unique advantages in external strong noise interference suppression, slurry flow measurement and low flow rate measurement.

3) With this technology, the fluctuation range of the flow signal can be controlled within 15mV, thus the slurry interference can be apparently weakened; the fluctuation range of the flow rate can be controlled within 0.030m/s. Particularly, the electromagnetic flow signal at a low flow rate ranging from 0.100m/s to 0.200m/s can be effectively extracted.

4) The method proposed in this paper can be extended to flow measurement under the condition of strong noise interference, slurry flow, and low flow rate.

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