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Time Delay Estimation in the Ultrasonic Flowmeter in the Oil Well

Jian Sun[a], Weijun Lin[a], Chengyu Zhang[a]*, Zhihui Shen[a], Hailan Zhang[a]

[a] *State Key Laboratory of Acoustics, Institute of Acoustics, Chinese Academy of Sciences, 21 Beisihuanxilu, Beijing 100190, P.R. China*

Abstract

A new prototype of ultrasonic flowmeter used in the oil well is presented. The flowmeter depends on the time delay between the propagating times of the downstream and upstream ultrasonic pulses. The ultrasonic passageway is slanted to prevent the disadvantage introduced by the high viscosity of the oil. Two method of time delay estimation: threshold and cross-correlation are both studied and realized.

Keywords: cross-correlation; oil well; threshold; time delay estimation; ultrasonic flowmeter

1. Introduction

In the oil field, it is reported that high viscosity and dielectric characteristics of the crude oil in wells of oil field cause difficulty for the traditional turbine and electromagnetic flowmeters. We designed a prototype of ultrasonic flowmeter to monitor the flow rate in the oil well in real time in conditions of high temperature up to 150 ℃ and high pressure up to 100*MPa*.

Flow rate is an important parameter for well logging in both injection profile and production profile. In the injection profile logging, flow rate shows the water absorption in different layers of water injection wells, so that the water injection scheme could be improved. In the production profile logging, flow rate combined with the water content or other logging parameters determine the different phase flow rate, which is helpful for the improvement of the exploitation scheme.

Because the ultrasonic flowmeter doesn’t have any mechanical friction, and is almost not affected by the oil contamination, it is suitable to work downhole[1].

There are two kinds of principle of normal ultrasonic flowmeter: time delay method and Doppler method. Our prototype chose the time delay method, which can have high precision and wide dynamic range to suit the flow rate of 3 m^3/day to 120 m^3/day, in other words the speed of 1.3 *mm*/*s* to 789 *mm*/*s*.

* Corresponding author. Tel.: +86-10-62559772; .
E-mail address: zhanghl@mail.ioa.ac.cn.

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2. Prototype

In order to work in the oil well, our prototype is designed as a cylinder with the diameter of 45 *mm* to work in the oil well with the diameter from 150 *mm* to 210 *mm*.

Two transducers, A and B shown in Fig.2, are mounted in the prototype act as transmitter and receiver to get the time delay between the propagating times of the downstream and upstream ultrasonic pulses. It is reported that when the ultrasonic transducers are placed in a straight direction in the flowmeter, as showing in Fig.1, the flow field between the transducers would be different from that outside the flowmeter, leading the time delay not reflected with the real flow rate. Besides, the oil contamination may be attached to the transducer, leading to a decrease of the signal-noise ratio (SNR).

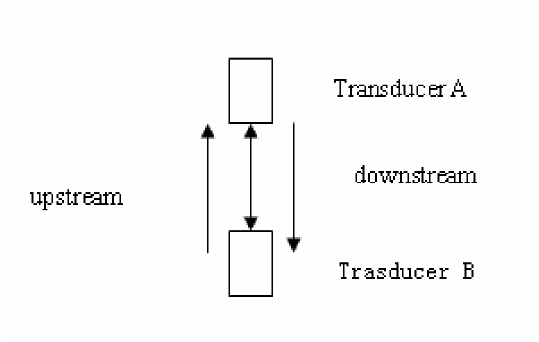

Fig.1 Illustration of the transducer placed in a straight direction.

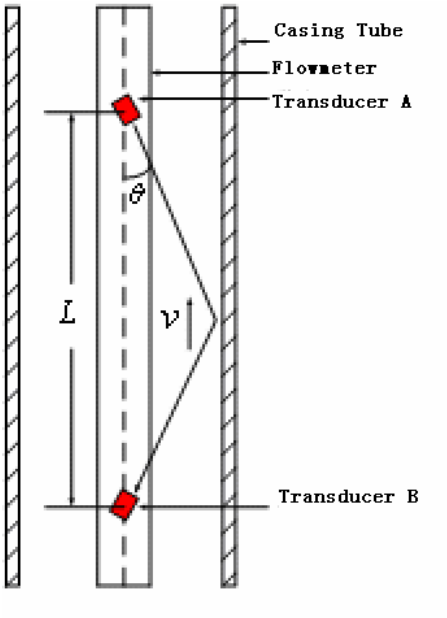

Fig.2 Illustration of mechanical structure of our prototype

In order to get rid of these disadvantages, we placed the transducers in a slant direction [2, 3], and in a short section to isolate the transducers from the oil. As showing in Fig.2, the ultrasound emitted by transducer A is send out of the flowmeter from a acoustic window, then reflected by the casing tube, and finally received by transducer B from the other acoustic window. Later exchanging transducer A, B as the emitter and receiver could get the propagating times of the downstream and upstream ultrasonic pulses. Let the distance between the transducers be L, the angle between the slant direction of the transducers and the axis of the flowmeter be θ, the flow speed be v and the sound speed be c, then the downstream and upstream propagating times are

$$t_d = \frac{L}{c + v\sin\theta}, t_u = \frac{L}{c - v\sin\theta} \tag{1}$$

and the time delay is

$$\triangle t = t_u - t_d \approx \frac{2vL}{c^2} (v \ll c) \tag{2}$$

Therefore we can estimate the flow rate by flow speed through the time delay between the downstream and upstream ultrasonic pulses:

$$v \approx \frac{c^2 \Delta t}{2L} \tag{3}$$

3. Simulation

When the flow rate is low to 3 m^3/day, the time delay may be less than 1 *ns* (L=0.5 *m*). In our prototype, the central frequencies of the 2 transducers are 750 *KHz*. The waveform is shown in Fig.3**.** Therefore the time delay estimation is needed with high precision.

We use both threshold and cross-correlation methods to estimate the time delay. The threshold method is that first set a threshold to fix the same cycle of the downstream and upstream pulses, then find the next zero-cross point as the propagating time, and finally calculate the time delay.

In practice, in the presence of noise, the choice of threshold is very important to make sure that the time delay would not be from different cycle of the downstream and upstream pulses. Fig.3 shows an example of wrong cycle checking.

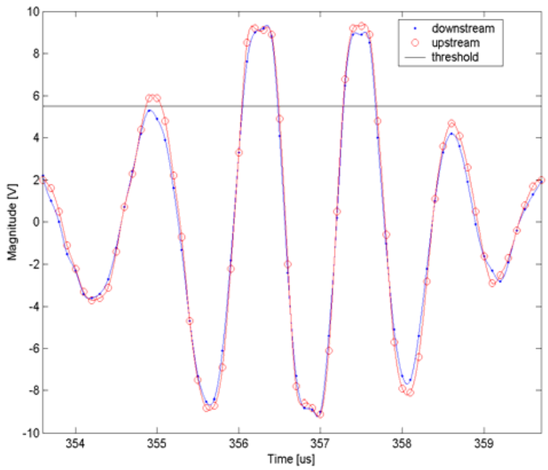

Fig.3 Example of wrong cycle checking

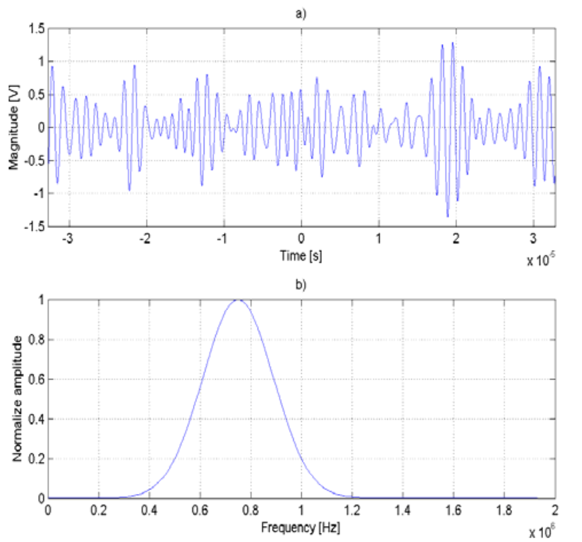

Fig.4 a) Noise waveform; b) Normalized amplitude spectrum of noise

To find out the best choice of threshold, a simulation is given below:

1. Generate a pulse of Gaussian envelop;
2. Generate 1000 noise seeds with the same bandwidth and Gaussian distribution, shown in Fig.4;
3. Add the noise seeds with different SNR (-30 *dB* to 30 *dB* with step of 3 *dB*) to the pulse; SNR is defined as[4]:

$$SNR = \frac{\text{peak instantaneous signal power}}{\text{noise power}} \tag{4}$$

4. Choose different threshold (0% to 100% of the amplitude of the pulse with step of 5%) to detect the propagating time.
5. Find out the range of SNR and threshold, where the wrong cycle checking would not occur even once in 1000 tests.
6. Calculate the bias and the standard deviation of the time delay in 1000 tests.

The simulation result shows:

1. From Fig.5, to avoid wrong cycle checking, it is required that SNR>15 *dB* and threshold should be 70~80% of the amplitude of the pulse;
2. In the above conditions, bias of the propagating time would be less than 20 *ns* and the standard deviation fluctuates from 10 *ns* to 20 *ns*.

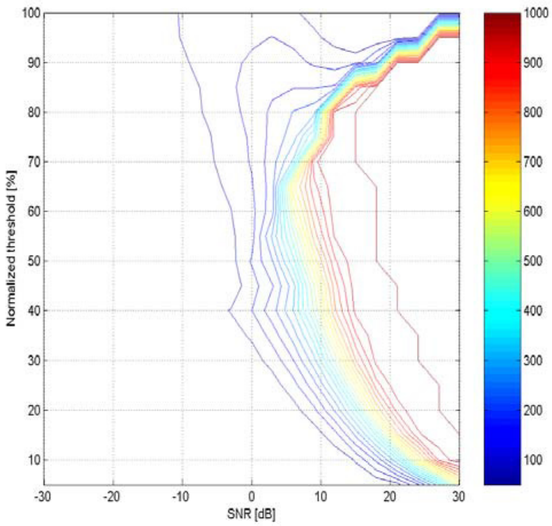

Fig.5 Right cycle checking result in 1000 tests versus SNR and threshold.

The cross-correlation method [5-8] assumes that the waveforms received by 2 transducers are

$$x_d(n) = s(n) + w_1(n) \tag{5.1}$$

$$x_u(n) = s(n-\tau) + w_2(n) \tag{5.2}$$

where $s(n)$ is signed the pulse, and $w_1(n)$, $w_2(n)$ are uncorrelated noise. The cross-correlation of $x_d(n)$ and $x_u(n)$ is

$$R_{du} = R_{ss}(n+\tau) \tag{6}$$

where $R_{ss}(n)$ is the correlation of $s(n)$ and the peak of R_{du} is at $n=-\tau$. We can estimate the time delay from the peak value position of the cross-correlation of the downstream and upstream pulses.

The simulation for the cross-correlation method is given below to show how SNR influence the bias and standard deviation of the time delay estimate by the cross-correlation method:

1. Generate a pulse of Gaussian envelop;
2. Generate 1000 noise seeds with the same bandwidth and Gaussian distribution;
3. Add the noise seeds with different SNR (-30 *dB* to 30 *dB* with step of 3 *dB*) to the pulses;
4. Set different time delay between the downstream and upstream pulses (from 0 to 200 *ns* with step of 10 *ns*), and use the cross-correlation method to estimate the time delay.
5. Calculate the bias and the standard deviation of the time delay in 1000 tests.

Fig.6 and Fig.7 show the simulation result:

1. When SNR>21 *dB*, the bias and the standard deviation is nearly not influenced by the set time delay;
2. When SNR>21 *dB*, the bias would be less than 4 *ns* and the standard deviation decreases from 30 *ns* to 10 *ns* as the SNR increases.

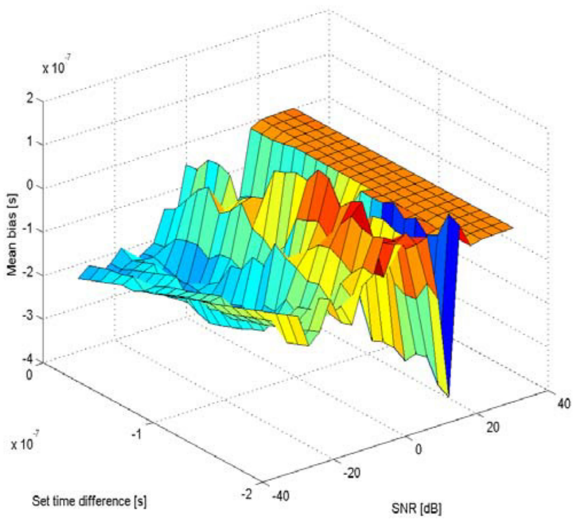

Fig.6 Bias of time delay estimation from cross-correlation versus SNR and set time difference

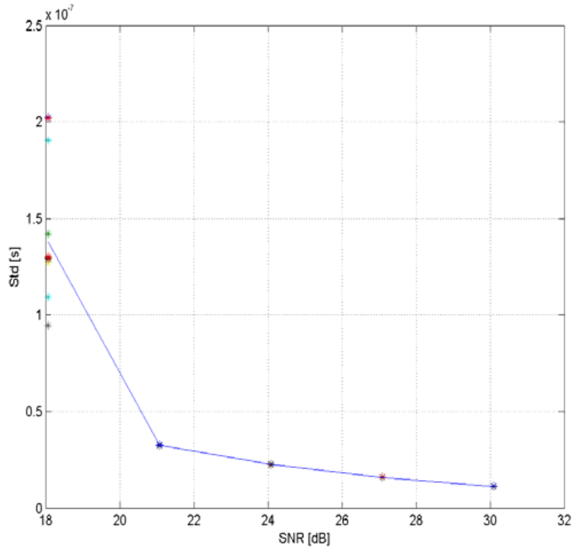

Fig.7 Standard deviation of time delay estimation from cross-correlation versus SNR. Different colored points denote different set time difference. The line is mean of all points

4. Experiment

To compare with the simulation, we do some experiments in our lab system to test our prototype. The setup of the experiment is shown in Fig.8. It is composed of tubing, ultrasonic system, electrical system, computer, water tank, pump and regulator flowmeter.

The waveform received by transducers is sampled by an AD with sampling rate of 10 *MHz*, and then the data will be interpolated by 100 times to increase the estimation precision and finally the time delay will be calculated by both methods. All the work is done in the electrical system and the time delay will be sent to the computer.

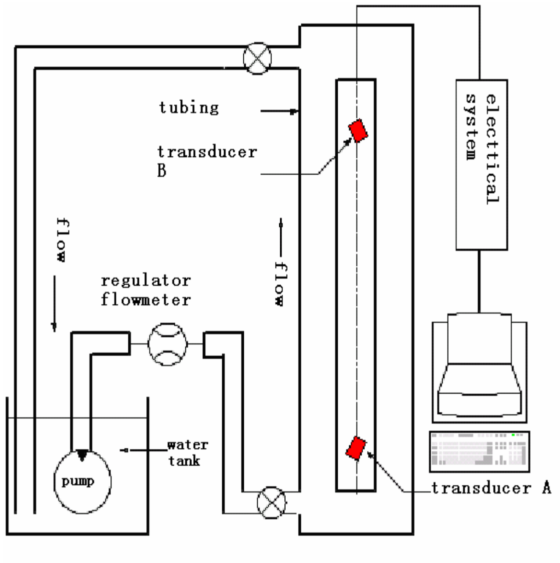

Fig.8 Setup of experiment

The experiment result is

When the flow rate is 0.08 *m/s*, in the threshold method around 10% of tests have wrong cycle checking, while it didn't occur in the cross-correlation method.

5. Conclusion

A new prototype of ultrasonic flowmeter used in the oil well is presented. Based on simulation and experiment, we find out that compared with the threshold， the cross-correlation method has higher precision and stability. In our prototype the precision can reach 10 *ns*.

Acknowledgements

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