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FLOW RATE CONTROLLING USING PHASE-LOCKED LOOP

KRIANGSAK PROMPAK¹, ANUCHA KAEWPOONSUK¹, THONGCHAI MANEECHUKATE¹
WASU PHANPHAISARN² AND PARAMOTE WARDKEIN³

¹Department of Physics
Faculty of Science
University of Naresuan
Phitsanulok 65000, Thailand
mum.c51@hotmail.com; { anuchak; thongchaim }@nu.ac.th

²Department of Physics
Faculty of Science and Technology
University of Piboonsongkram Rajabhat
Phitsanulok 65000, Thailand
wasu.phy@hotmail.com

³Department of Telecommunication Engineering
Faculty of Engineering
King Mongkut's Institute of Technology Ladkrabang
Bangkok 10520, Thailand
pramote@telecom.kmitl.ac.th

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ABSTRACT. *This paper proposes controlling flow rate by using Phase-Locked Loop (PLL) to control the voltage output of power amplifier sent to the DC pump. With this technique, the flow rate of liquids in the pipe connected to such pump can be easily adjusted. With the property of PLL, the frequency of output signal of the flow sensor, which is proportional to the flow rate, is synchronized with that of the reference input. As a result, the flow rate remains constant. In addition, the experiment results show that the flow rate is not affected by the varying loads, i.e., the flow rate is stable to perturbations.*
Keywords: Phase-locked loop, Flow rate, Control

1. Introduction. The measurement of fluid flow is very important in industrial applications. Some equipment and operations require specific flow rates for working efficiently. The cost of many liquids and gases is based on the measured flow through a pipeline. Thus, it is necessary to accurately measure and control the rate of flow for accounting purposes.

In the measurement and control system when a change in a measured variable with respect to a reference has been sensed, it is necessary to apply a control signal to an actuator to make corrections to an input controlled variable, via a value bringing the measured variable back to its preset value. In most cases, any change in the variables (e.g., temperature, pressure, and level) can be corrected by controlling flow rates.

Conventionally, the flow rate control can be achieved by an analog servo feedback system [1] in which any change in flow rate is sensed and compared with a fixed reference voltage to generate a correction signal. However, this analog feedback system is not satisfactory in some application where excellent speed regulation and fast dynamic response are required. These features can be achieved by using a PLL control system [2,3].

PLL is a feedback loop where a voltage-controlled oscillator can be automatically synchronized ("locked") to a periodic input signal. The locking property of the PLL has numerous applications in communication system (such as frequency, amplitude, or phase

modulation/demodulation, analog of digital), tone decoding, clock and data recovery, self-tunable filters, frequency synthesis, motor speed control [4], etc.

This paper presents the PLL circuit used to control the flow rate, the flow rate is converted to a pulse train by the flow sensor, which is synchronized with a reference pulse train. In this way, by locking onto a reference frequency, precise control of the flow rate is achieved.

This paper is organized as follows. The principle of PLL and voltage controlled oscillator (VCO) obtained by combination of the flow sensor and the DC pump are first described in Section 2. The proposed flow rate control system using PLL is presented in Section 3 where experimental results for controlling flow rate of water are demonstrated in Section 4. Finally, Section 5 is devoted to the conclusion.

2. Principle.

2.1. Phase-locked loop (PLL). The basic functional components of a PLL are: a VCO, a phase detector (PD), and a loop filter (LF).

The interesting signals in the PLL block diagram shown in Figure 1 are defined as follows: the reference (or input signal) $v_1(t)$ with an angular frequency ω_1 , the output signal $v_2(t)$ of the VCO with an angular frequency ω_2 , the output signal of the phase detector $v_d(t)$, the output signal $v_f(t)$ of the loop filter, and the phase error θ_e , defined as the phase difference between signals $v_1(t)$ and $v_2(t)$.

The VCO oscillates at an angular frequency ω_2 which is determined by the output signal $v_f(t)$ of the loop filter. The angular frequency ω_2 is given by

$$\omega_2 = \omega_0 + K_0 v_f(t), \quad (1)$$

where ω_0 is the centre frequency of the VCO and K_0 is the VCO gain. The PD compares the phase of the output signal with the phase of the reference signal and generates an output signal $v_d(t)$ that is approximately proportional to the phase error θ_e , the former signal is given by $v_d(t) = K_d \theta_e$, $\theta_e \rightarrow 0$, where K_d represents the gain of the PD. The output signal $v_d(t)$ consists of a DC component and a high frequency ac component. Since the latter is undesired, it is cancelled by the loop filter. Assuming the angular frequency of the input signal $v_1(t)$ is equal to the centre frequency ω_0 , the VCO then operates at its centre frequency ω_0 , and the phase error is zero, indicating the output signal of the loop filter $v_f(t)$ is also zero. If the phase error θ_e was not initially zero, the PD would develop a nonzero output signal $v_d(t)$. After some delay, the loop filter would also produce a finite signal $v_f(t)$, which will cause the VCO to change its operating frequency in such a way that the phase error finally vanishes, and after some settling time the VCO will oscillate at a frequency that is exactly the frequency of the input signal.

From the above description the PLL can be interpreted as a particular example of a driven oscillator [5].

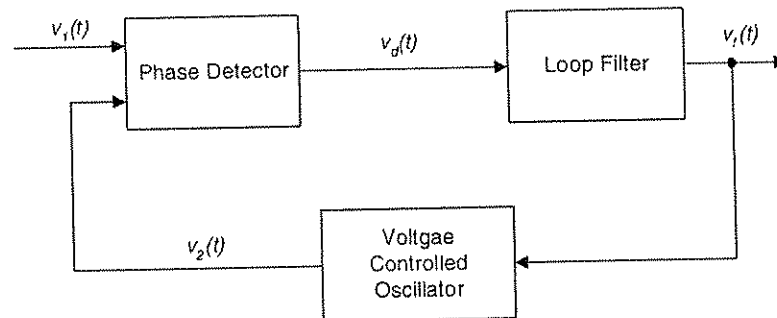


FIGURE 1. Block diagram of the PLL

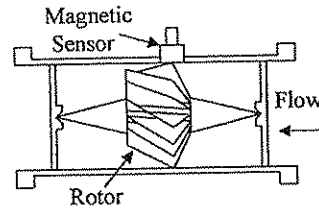


FIGURE 2. Flow rate measurement sensor

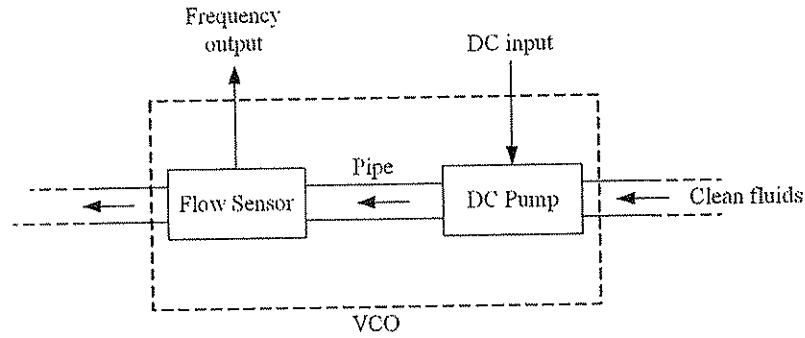


FIGURE 3. The VCO built by connecting the flow sensor with the DC water pump

2.2. Flow sensor connected to DC pump: VCO. An example of flow rate sensor is the turbine flow meter, which is shown in Figure 2. The turbine rotor is mounted in the center of the pipe and rotates at a speed proportional to the rate of flow of the fluid or gas passing over the blades. The turbine blades are normally made of a magnetic material or ferrite particles in plastic so that they are unaffected by corrosive liquids. As the blades rotate they can be sensed by a Hall device attached to the pipe. Thus, the signal generated by Hall sensor has a frequency proportional to the flow rate of liquids. The turbine should be only used with clean fluids such as gasoline.

If a DC pump is connected together with the flow rate sensor described above by the pipe as block diagram shown in Figure 3; hence, it can be considered as a VCO, which the voltage at the input of this VCO, namely the voltage at the input of the pump, determines the frequency f_{osc} of the periodic signal at the output of the VCO, the frequency of the output of flow sensor.

Next, a relation between the flow rate Q and the input voltage V_{in} of the pump can be considered as

$$Q = K_p V_{in} + a, \quad (2)$$

where K_p is the pump gain and a is constant, and a relationship between the angular frequency of output signal of the flow sensor ω and the flow rate Q can be considered as

$$\omega = K_s Q + b. \quad (3)$$

where K_s is the gain of the flow sensor and b is constant. Substitution of Equation (2) in Equation (3) gives

$$\omega = K_p K_s V_{in} + c. \quad (4)$$

It is easy to see that Equation (4) corresponds to Equation (1) above where $K_0 = K_p K_s$ and $\omega_0 = c = a + b$.

3. The Proposed Circuit. An example of liquids used in this paper is water. In order to control flow rate of water inside the pipe by using circuit based PLL, it is important that the phase of output signal of the flow sensor must be synchronized with every cycle of the controlling signal. With synchronization property of the PLL, the proposed circuit is

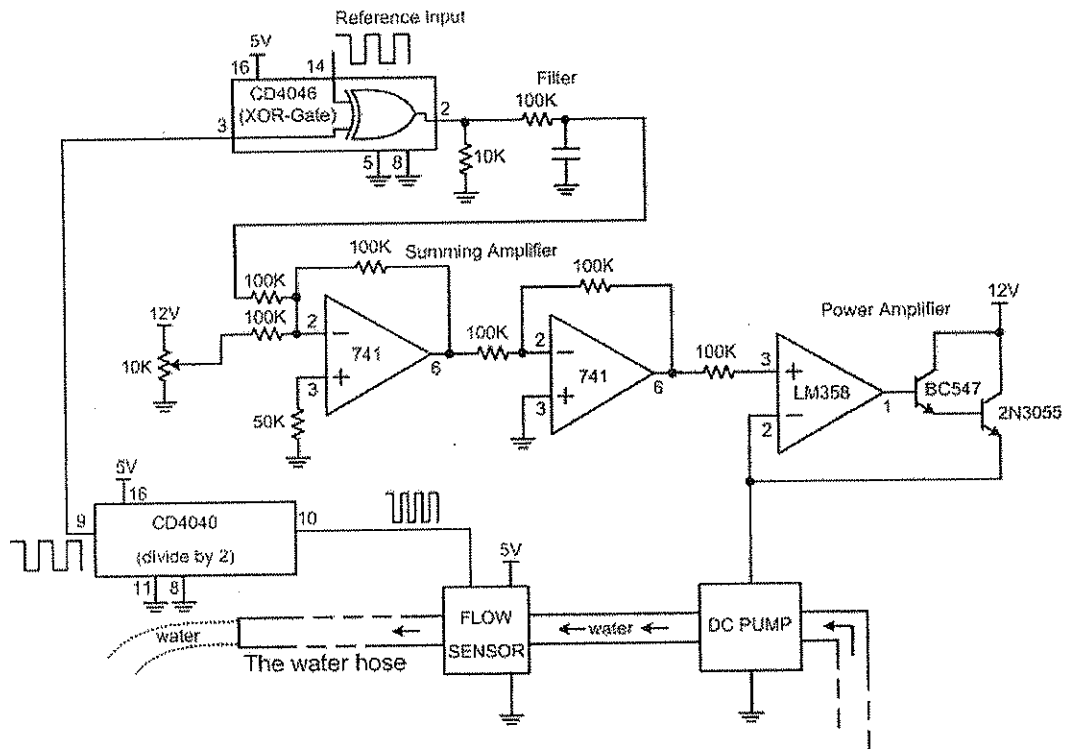


FIGURE 4. The proposed PLL circuit

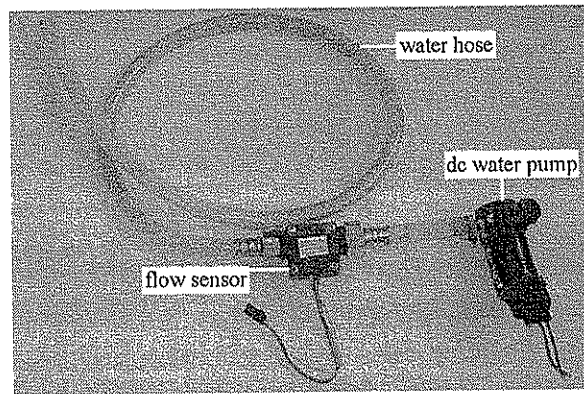


FIGURE 5. The DC pump connected together with the flow rate sensor by water hose

therefore insensitive to varying of the load. Based on the described principle of controlling flow rate, block diagram of the propose circuit can be depicted in Figure 4. From circuit in Figure 4, the reference signal $v_1(t)$ from generator is connected to one of the two inputs of the phase detector on the CMOS 4046 chip. The phase detector on the 4046 is simply an XOR logic gate. The output $v_d(t)$ of the phase detector is filtered by a low-pass filter; here the loop filter is a simple passive RC filter. From the principle of the PLL, the VCO, implemented by combination of DC pump and the flow sensor, must be still running at frequency f_0 when there is no difference between phase of the reference signal and of the VCO output, i.e., the control voltage $v_f(t)$ is zero; in order to do this, a summing amplifier is used to add DC signal to the filter output $v_f(t)$, and then, its output is amplified by a power amplifier whose output drives DC pump. Next, the output signal of the flow rate sensor is connected to the input of a frequency divider on the 4040, whose output is

connected to the other one of inputs of the phase detector on the 4046. The frequency divider that is employed within the loop reduces the reference frequency; here, a frequency divider by 2 is designed.

4. Experimental Results. The system is built and tested with a mini DC water pump (12V, 7L/min) and the water flow sensor, YF-G21 (In datasheet of this flow sensor it describes that flow rate can be calculated directly by the equation $Q = f_{osc}/7.5$, where Q is flow rate in L/min (Precision 3% in the interval 1 L/min to 10 L/min) and f_{osc} is pulse frequency (Hz) in horizontal test). Here, the VCO is implemented by combination of such DC pump (with the pump driver) and flow sensor, as illustrated in Figure 5. The relationship between the voltage at input of such VCO and the frequency of its output signal is represented by a curve as shown in Figure 6. Note that the frequency is proportional to input voltage.

Next, to verify the proposed principle, laboratory experiment of the proposed circuit, as shown in Figure 4, is set up. In the experiment the frequency of the reference signal is 4.0 Hz, i.e., the required flow rate is about 1 L/min; then, the load acting on the system can be easily varied by lifting the free end of water hose up vertically in the air, which is divided into 2 different levels; the first level is lower than the second one, but in each

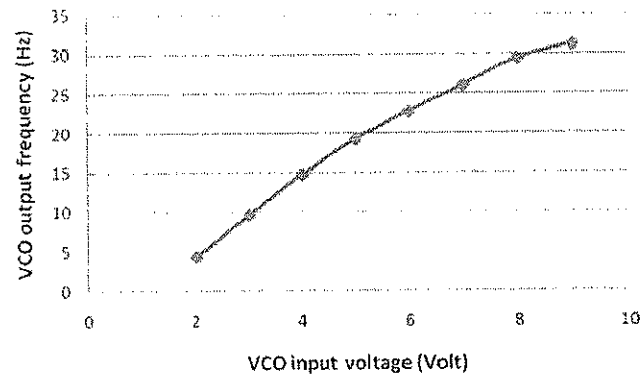
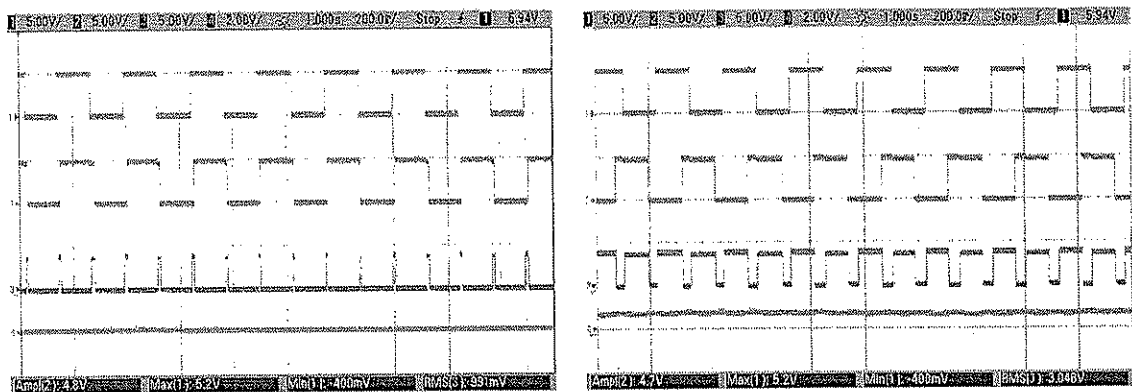


FIGURE 6. The relation ship between voltage at the input and frequency of the VCO output signal



(a)

(b)

FIGURE 7. The results of experiment from putting the free end of water hose at the first level (a) and the second level (b); the second level is higher than the first one

level the frequency of the output of VCO (divided by 2) remains the same as that of the reference input, namely 4.0 Hz.

The obtained signals are shown in Figures 7(a) and 7(b). In each figure the upper trace is the reference input signal, the second trace is the output signal of the frequency divider, the third trace is the output of PD, and the last trace is the output signal of the low-pass filter. Note that when the free end of water hose is raised higher than ever, the duty cycle of the output of PD increases; and the voltage output of the loop filter also increases, which is amplified to drive the pump. As a result, the frequency of the output of VCO (divided by 2) remains the same as that of the reference input, i.e., the flow rate of water does not change. From this experiment it illustrates that the system is stable to perturbations.

5. Conclusions. In this article, controlling flow rate by using PLL has been proposed. The main advantages of the proposed circuits are 1) the flow rate can be electronically controlled by DC input signal and 2) it is stable to perturbations due to synchronization property of the PLL. The experimental results have illustrated that the proposed principle can be applied for fluid flow rate controlling. In the future, we want to develop this system by adding the reference frequency circuit that we can select the wanted reference frequency from it.

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