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Design and development of an electronic level transmitter based on hydrostatic principle

S. Faizan Ali, N. Mandal *

Indian Institute of Technology (ISM), Dhanbad, Department of Electronics Engineering, Dhanbad 826004, Jharkhand, India

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A B S T R A C T

Diaphragm is a pressure transducer which is used as a primary sensing element for hydrostatic liquid level measurement. In industry, it can be used as a local display unit. Diaphragm reading can be transmit to a remote location with the help of secondary transducer which converts the diaphragm displacement into an electrical signal. In this paper, a simple low cost hydrostatic liquid level transmitter has been developed with diaphragm as a primary transducer and Hall sensor as a secondary transducer. The theoretical analysis of the work has been presented in this article. The theoretical equation describes the working principle of the proposed transmitter. The experimental setup has been developed in the laboratory and tested over a range of 0–100 cm. The static characteristic of the hydrostatic level transmitter shows that the transmitter follows the theoretical equation. The experimental results reported in this paper show that the transmitter characteristics are linear and repeatable under permissible uncertainty range.

1. Introduction

Hydrostatic liquid level measurement in a container or tank is an important aspect in process industries. Common level measurement systems are based on radar, ultrasonic, electromechanical, capacitance principles [1–3]. Various liquid level measurement methods are available but accurate and reliable liquid level measurement technique is important in the process industry. There are different types of works have been reported in the development of liquid level measurement. Vargas et al. [4] have discussed the ultrasonic method for measurement of liquid level in bottles. This ultrasonic sensor is based on the time of flight principle which can measure the height of the liquid level without having to contact with the liquid. Ultrasonic based level measurement is a well-established technique, but it suffers from changes in sound velocity. Musayev et al. [5] have discussed an optical method for level measurement that use an LED and a photo transistor which is placed reciprocally with a shaft in their optical axis. Canbolat [6] has proposed a method for liquid level measurement using three parallel plate capacitors to eliminate the effect of air dielectric and temperature. A contactless liquid level measurement method [7] has been presented by Tatsuo Nakagawa et al. in which a millimeter-wave sensor is used to sense and measure the height of the liquid level. The system parts should have good reflection property otherwise the sound waves are scattered. A truly nonintrusive optical sensing method based on the phenomenon of lateral displacement effect for measurement of liquid level has been proposed by [8]. In this method, the lateral displacement is observed when the oblique light ray passes through the different thickness and refractive index in the material medium. If there are gas bubbles in the liquid, the waves are scattered through the bubbles. The scattering effect is yet another drawback. Alexander Jahn et al. [9] have introduced the design and implementation of a novel approach to determine the liquid level using one piezoelectric transmitter and one piezoelectric receiver. The system shows a simple, low cost, efficient, non-destructive and non-intrusive sensor to monitor the fluid level continuously. The major drawback of this system is that it is not suitable for static measurement. Liquid level measurement using two wire probe depend on time-domain reflectometry (TDR) method has been developed in [10]. This method is based on the electromagnetic (EM) signal propagation through a probe which is attached to the outside wall of the container. This method may be used for non-invasive monitoring and measurement of liquid level in industry. Jin et al. [11] have developed a liquid level measurement system depends on coaxial cylindrical capacitance sensor in which the outer conductor is used for liquid level measurement whereas the inner conductor is connected to the ground. This system is used only for conducting liquid. Intrinsically safe liquid level sensor has been developed using PVC (Poly Vinyl Chloride) coaxial cable [12]. Here, the optical

* Corresponding author.
E-mail address: nirupama_cal@rediffmail.com (N. Mandal).

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Nomenclature

Symbols	Explanations
ΔP	Hydrostatic pressure, N/m^2
B_h	Magnetic field intensity, gauss
V_h	Hall sensor output voltage, mV
x	Displacement of diaphragm, mm
h	Height of the liquid in the tank, cm
V_0	Signal conditioner output voltage, V
I_0	Current signal 4-20 mA
ρ	Density of the liquid in the tank , kg/m^3
g	Acceleration due to gravity, m/s^2
r	Radius of the circular magnet, mm
$K_1, K_2, ..., K_{11}, p, q$	Constant terms

transmission is preferred over electrical signal for flammable and explosive environment. A capacitive sensing system has been designed and developed by Bowen Wang et al. for the car washer liquid level measurement [13]. The sensor used is capable of detecting the liquid level in the car washer tank in contrast to the permittivity difference between air and water. Kumar et al. [14] have developed level-transmitter consisting of two electrode for level measurement and electro-optic system using Mach-Zehnder interferometer for transmitting the voltage signal output of the proposed transducer to the remote place. The transmission through optical network is very costly which cannot be preferred in the industry. Simultaneous measurement of temperature and liquid level using optical fiber have been developed by the integration of Fiber Bragg grating (FBG) with no-core fiber (NFC) [15]. The liquid level detection with temperature compensation has been achieved by utilizing the temperature sensing property of FBG.

Hydrostatic liquid level transducer is used for the measurement of liquid level in terms of hydrostatic pressure developed at the bottom of the container or tank. Hydrostatic level measurement systems are based on the principle that the pressure is directly proportional to the liquid column above the pressure sensor. In hydrostatic level measurement, despite of the shape and volume of the container or tank, the hydrostatic pressure at the measuring point of the container is directly proportional to the height of the tank. In hydrostatic liquid level measurement, the measured level signal is required to send to some remote place, so that it can be easily and accurately supervised. The primary sensor signal must be converted into an electrical signal so that it can be easily send to the remote location. Transducer such as piezoelectric transducer, strain gauge, linear variable differential transducer and capacitive element [16,17] can be used as secondary transducer. Diaphragm, basically a pressure sensor can also act as primary sensing element for hydrostatic level measurement. Diaphragm is placed near the bottom of the storage tank and measure the height of the liquid level in terms of hydrostatic pressure developed at that point. Morris et al. [18] have presented a curved piezoelectric diaphragm displacement measurement in which curved piezoelectric diaphragm transducer provides high displacement amplitude and a low frequency mode that is useful to the surrounding acoustic medium for efficient coupling. Ameen et al. [19] have developed a graphene diaphragm integrated silica Fiber Bragg grating (FBG) for detection of water level and temperature. The graphene diaphragm on immersing inside the water gets deformed due to hydrostatic pressure imposed by the water level. A thin film residue is left on the sensor which limits the capability of the sensors. In the diaphragm based measurement technique, secondary transducers are used to convert the displacement of diaphragm into an electrical signal. Combination of Hall sensor and magnet can act as a very good secondary transducer for such type of requirement. McCall et al. [20] have designed a circuit for linear position measurement using Hall sensor and also remove the nonlinearity due to magnetic field. The circuit design is applicable only for very short range of linear motion. In [21], Hall effect based noncontact pressure transmitter has been designed with good repeatability. The bellows has been used as primary transducer and Hall probe sensor as secondary transducer.

In the present work, the level of liquid is measuring with hydrostatic level transmitter by fabricating of diaphragm sensor with Hall sensor to improve the accuracy as well as reliability and cost of the liquid level measurement system as compared to the existing ultrasonic, laser and radar type level transmitter. Diaphragm is acting as a primary sensor and Hall sensor is acting as secondary sensor for measurement of hydrostatic liquid level. In this work, a diaphragm is attached at the bottom of the glass chamber and inside the chamber, a permanent magnet is placed at the centre of the diaphragm. The glass chamber is connected with the rod at the top of the chamber and the glass chamber is placed inside the liquid tank. The Hall probe is placed top inner side of the glass chamber. When the liquid level of the tank increases, the hydrostatic pressure which is acting at the bottom of the chamber increases also, then the distance between the magnet and the Hall sensor decreases as diaphragm is displaced from the bottom of the tank. The Hall sensor output voltage increases since the intensity of the magnetic field increases due to the increase in hydrostatic liquid level. Thus, Hall voltage increases with the increase of level of the liquid. In the proposed design, A3144 Hall sensor is used. The change of magnetic field due to the small displacement by the diaphragm is sensed by the Hall sensor and is expected to lie within the linear range. Hence, the static characteristic of the hydrostatic liquid level system has been observed to be linear. The mathematical equations are derived to explain the theoretical operation of the proposed liquid level measurement system. The proposed hydrostatic liquid level measurement setup has been developed and tested in the laboratory. The experimental result reported in this paper shows that the transmitter characteristics are linear and repeatable under permissible uncertainty range.

2. Method of approach

In this work, the diaphragm is acting as a primary transducer which converts the hydrostatic pressure due to height of the liquid level into linear displacement as presented in Fig. 2. In hydrostatic liquid level, the hydrostatic pressure is created at the bottom of the container or tank.

Let the hydrostatic pressure be ΔP and the height of the liquid level be h. So, the hydrostatic pressure is given by,

$$\Delta P = \rho g h \tag{1}$$

where ρ is the density of the liquid in the tank and g is the acceleration due to gravity. Since ρ and g are constant. Hence, Eq. (1) can be written as,

$$\Delta P = K_1 h \tag{2}$$

A diaphragm is attached at the bottom of the glass chamber which is located inside the tank as shown in the Fig. 1. When the hydrostatic pressure is created at the bottom of the tank then the diaphragm is displaced. Let the displacement at the centre of the diaphragm in its elastic region be x.