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Brief paper

Capacitive sensor-based fluid level measurement in a dynamic environment using neural network

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ABSTRACT

A measurement system has been developed using a single tube capacitive sensor to accurately determine the fluid level in non-stationary tanks, namely automotive fuel tanks. The system determines the fluid level in the presence of dynamic slosh. A neural network-based approach is used to process the sensor signal and achieve substantial accuracy compared with the averaging method, which is normally used under such conditions. The sensor readings were obtained by experimentation carried out under various dynamic conditions. The sensor response was recorded at various slosh frequencies and fuel volumes; which was then used to train three different neural network topologies. Field trials were carried out to obtain the actual driving data for the purpose of testing the neural networks using MATLAB software. One static neural network topology, namely Feed-forward Backpropagation Neural Network, and two dynamic neural network topologies, namely Distributed Time Delay Neural Network and NARX Neural Network, have been investigated in this work. The developed fluid level measurement system is capable of determining the fluid level in a dynamic environment with a maximum error of 8.7% by using the two dynamic neural networks, and 0.11% using the static feed-forward back-propagation neural network.

1. Introduction

Capacitive sensors are increasingly becoming a substitute for the mechanical devices in the industrial and automotive applications, as they provide the benefits of long-term reliability even in hostile environments. A capacitive sensor has no moving parts. It determines the fluid level based on the changing capacitance value. The capacitance depends on the dielectric constant, the area of the conducting plate, and the separation distance of the plates. If the properties of a capacitor remain fixed, except for its dielectric constant, then the capacitance in terms of its dielectric constant can be calculated as follows:

$$C(\varepsilon_r) = \varepsilon_r \left(\frac{\varepsilon_0 A}{d} \right) \tag{1}$$

where C is the capacitance in farads (F), ε_y is the relative static permittivity (dielectric constant) of the material between the plates, ε_0 is the permittivity of free space, A is the area of each plate in square metres, and d is the separation distance of the two plates.

The capacitance value is proportional to the dielectric constant of the material that separates the two conducting plates (Serway and Jewett, 2004). Therefore, any change in the fluid level will correspond to a change in the dielectric constant, hence the capacitance value.

The fluid level measurement will experience error in level readings for applications where the storage tank is non-stationary, such as an automotive fuel tank. Due to the nature of the driving conditions, a fuel tank is normally subjected to acceleration, which induces slosh waves in the fuel tank. A level sensor might erroneously sense these fluctuations in the fluid to be the actual levels of the fluid, thereby producing inaccurate fluid level reading.

A fuel tank may contain contaminants and could also experience variations in the temperature. Results from the Design of Experiments (DOE) have indicated significant effects of temperature variations and contaminants on the fuel level measurement. The influence of temperature variations along with contamination can result in shifts in the dielectric constants. The response of the sensors in such environments could be influenced by the environmental parameters in a nonlinear manner (Patra, 2004).

Several methods have been used to compensate for these dynamic effects. Kobayashi and Obayashi (1983) used an averaging method that simply averages the fuel volume signal during various vehicle conditions detected by the speed

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sensor. The averaging methods Kobayashi and Obayashi (1983), Tsuchida (1981), and Kobayashi and Kita (1982) could be useful in approximating the liquid level while the liquid fluctuates but it nevertheless gives inaccurate results especially at varying temperature levels. Fig. 1 shows the errors obtained using the averaging method in a fuel tank filled with 45 L of fuel at various levels of acceleration. Artificial Neural Networks (ANN) can be used to effectively solve such problems. Intelligent machines and sensors can be developed with neural networks that are obliged to operate in dynamic environment without compromising accuracy. Patra et al. (2008) and Song (2007) have used neural networks to develop intelligent sensors that compensate for the nonlinear environmental parameters.

This paper illustrates a neural network approach to determine the fluid level in a dynamic environment without compromising the accuracy. To reduce the complexity of the problem, the capacitive sensor was calibrated to the ambient temperature and fuel type; thereby the influence of temperature and contamination factors on the fluid level measurement could be ignored. The principal focus of this work is related to eliminating the effects of liquid slosh on fluid level measurement using an artificial neural network approach.

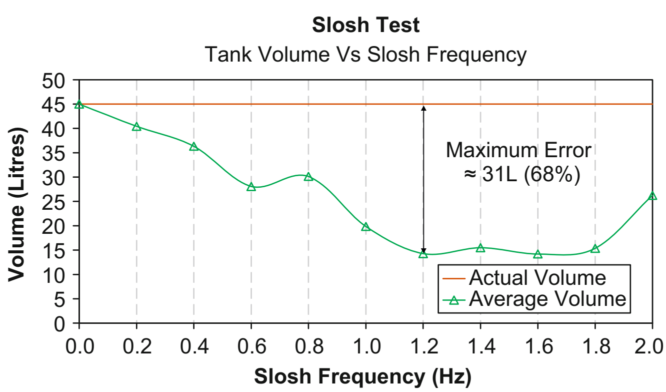

Fig. 1. Slosh test at various acceleration or slosh frequencies. The fuel level signal is averaged over a period of 10 s. Largest error was 31 litres or 68%.

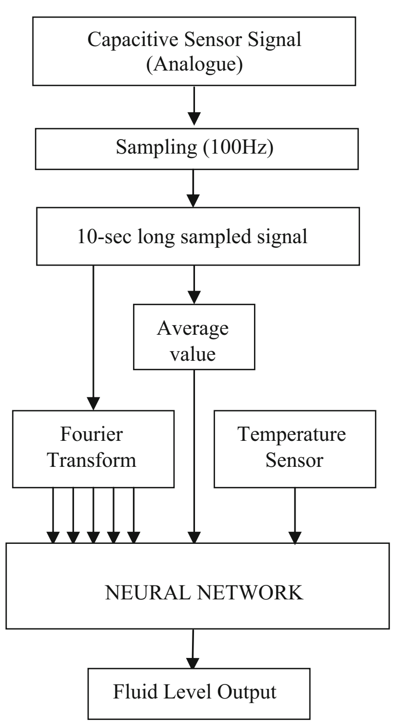

Fig. 2. System block diagram.

2. Neural network-based approach

A fuel tank containing fluid will exhibit slosh waves whenever the walls of the container experience acceleration (Wiesche, 2003). The induced slosh pattern will produce natural sloshing frequencies, which are associated with the shape of the storage tank and the existing quantity of the fluid. The capacitive sensor output will exhibit the slosh patterns produced in the fuel tank when it is sampled at a high sampling rate.

Artificial neural network can be trained with different signals signifying different slosh patterns to determine the actual fuel volume residing in the tank. Feature extraction is performed in signal pre-processing by applying Fourier Transformation on the raw sensor signal, which can reduce the size of the input data as well as increase the speed and performance of the neural network. A low-pass filter that eliminates high frequencies (over 150 Hz) is also applied in signal pre-processing. Fig. 2 illustrates the system block diagram that was used to develop the neural network approach to fluid level measurement.

An accumulated sampled signal of 10 s duration is converted into the following two forms, which is then fed into the neural network:

- Frequency response—representing slosh waves
- Average volume—representing average value of the fluid

The capacitive sensor was calibrated to the ambient fuel and temperature, therefore, the effects of temperature and contamination can be assumed as insignificant.

3. Network topologies

The following two commonly used network topologies are investigated in developing the presented neural network based fluid level measurement system:

- Static Feed-Forward Network
- Dynamic Networks (with and without feedback)

3.1. Static feed-forward network

Feed-forward Backpropagation (BP) neural network is the static network, where signals travel in one direction only, i.e. from input to output. There is no loop or feedback between neurons and their inputs and outputs, which makes them straight forward. Backpropagation network topology is extensively used in pattern recognition. Fig. 3 illustrates the structural diagram of the BP network that takes the signal features and produces the fluid volume figure as the output.

$$Volume(p) = purelin\lfloor LW(tansig(IW_p + b_1)) + b_2 \rfloor \quad (2)$$

where p is the input signal of length R; IW and LW are input and layer weights, respectively; $b_{1,2}$ are the bias values of each neuron. The network consists of S^1 number of neurons with tansig and purelin as the transfer functions.