

## Experimental Model-Based Simulation for Health Monitoring of a Non-Linear Liquid Level System

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### ABSTRACT

Due to new technologies, the improvement of industrial systems is progressively complex. Accordingly, it has become difficult to manage and predict the behaviour of these systems, particularly when they will be exposed to failures. An identical dynamic model should reflect all characteristics of a planned integrated mechatronic system. Health monitoring of any system is essential in guaranteeing the safe, efficient, and correct operation of complex engineering systems. This paper presents a simulation of a non-linear, experimental based model of a coupled tank apparatus CE 105 by using LabVIEW 2014. In this study, a common modelling paradigm with several sources of fault was used to simulate both nominal and faulty behaviour. It is concluded that the liquid level, in the presence of a PID controller, will not be affected by the fault value until it reaches a certain threshold. Hence, the end of the useful life could be predicted by monitoring the PID voltage.

*Keywords: nonlinear system; health monitoring; liquid level system; model based simulation*

### 1. Introduction

Liquid level systems have an extensive variety of industrial process applications, such as petrochemical industries, papermaking, water treatment industries, and power plants. For example, controlling a liquid level in a tank and consequently the free outflow rate by using Proportional- Integral- Derivative (PID) controller is of crucial importance for mixing reactant processes [4]. A liquid level system is commonly controlled by using a conventional PID controller. This feedback controller minimises error through regulating the process-controlled inputs, the pump voltage for example [6]. Ogata [7] stated that a liquid level system can be considered linear if the liquid outflow is laminar;  $Q = K h$ , where  $Q$  is a steady-state liquid outflow rate, [m<sup>3</sup>/sec],  $K$  is a coefficient [m<sup>2</sup>/sec] and  $h$  is a steady-state head, [m]. If the flow through the outlet valve is turbulent, the steady-state outflow rate is:  $Q = K\sqrt{h}$ . Ogata [7] also stated that if the flow is turbulent, the system can be linearized when the change in the variables are kept small. The square root characteristic is widely used to model the flow through hydraulic orifices. This may cause numerical problems because the derivative of the flow with respect to the pressure drop tends to infinity when the pressure drop approaches zero. Furthermore, it is more reasonable to assume that the relationship between the free outflow rate and the pressure drop is linear for small values of pressure drop [2]. Non-linearity is the nature of all real systems [5].

PID controller is a widely recognisable type of feedback controller. A PID controller calculates an "error" value as a difference between the required demand and the measured process or plant variable. The purpose of the controller is to minimise the error through regulating the process-controlled inputs as each element of the PID controller assigns a specific activity taken on the error [6]. The liquid level system is commonly controlled by using a conventional PID. The main reason for using a PID controller is on account of its simple structure and application.

The contribution reported in this paper relates to the simulation and experimental validation of a CE 105 coupled-tank liquid level control system. The consideration of this system is extended via the inclusion of non-linear elements in the simulation created using a real-time control toolbox within LabVIEW 2014. The simulation is used to accelerate the timescales of monitoring in order to have a prior knowledge of the system behaviour and track different operational scenarios. Furthermore, faults

diagnosis and the remaining useful life prediction could be achieved in advance. Results are reported and discussed for a leakage and reduced pump performance faults.

## 2. Description of the coupled tank system

The coupled tank apparatus CE 105 was selected to study its nominal and faulty behaviour. In this set-up, a PC with NI USB- 6008 DAQ and LabVIEW 2014 programme serves to control and manage the system, as shown in Figure 1.

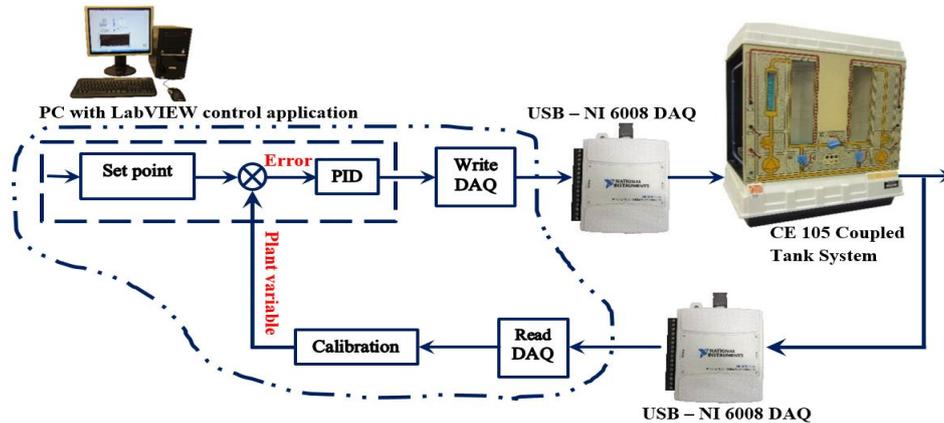


Figure 1: Schematic diagram of the system

## 3. Calibration equations

Open loop experimental tests were done on the CE105 apparatus in order to estimate the calibration equation of each single element of the system; the results are as shown in Figure 2.

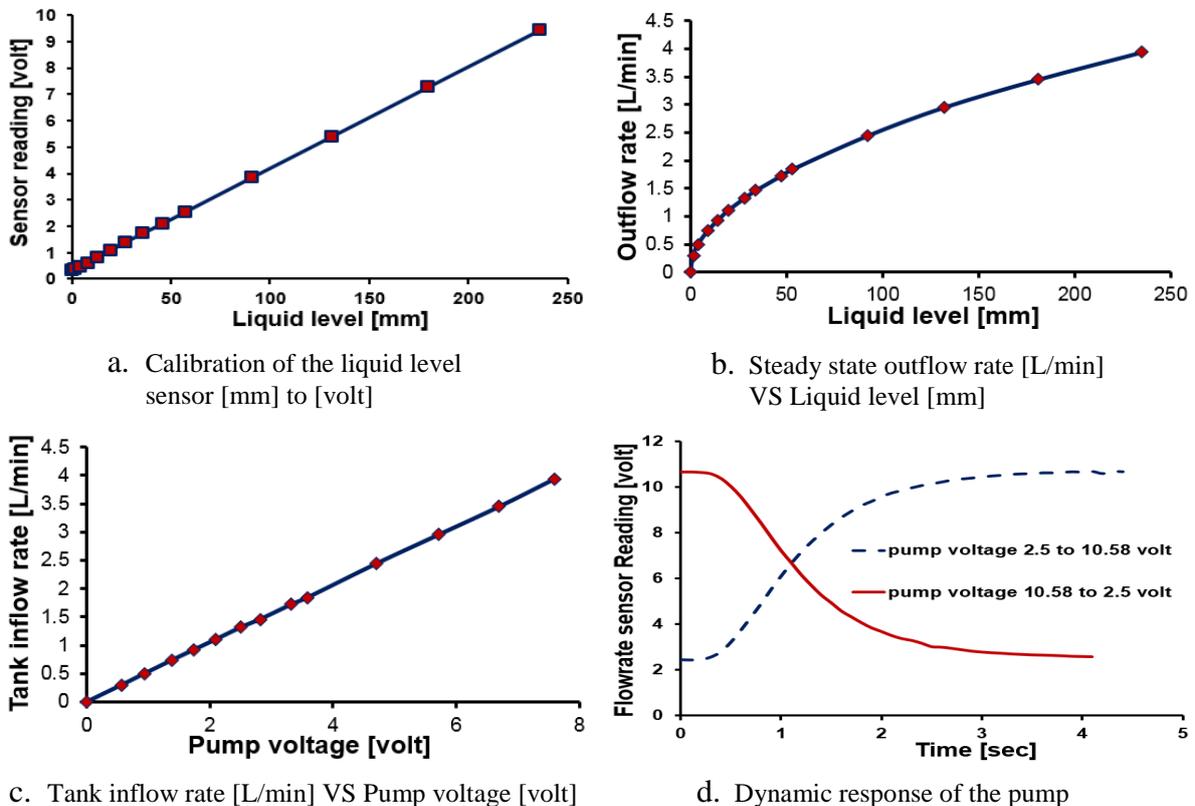


Figure 2: Calibration equations of the system elements

Calibration equations of liquid level and flow rate sensors are linear functions companion an offset terms as shown in equations 1 and 2 respectively.

$$y = 0.0386 x + 0.3231 \quad (1)$$

$$y = 2.0954 x + 0.2377 \quad (2)$$

Laplace transformation of the liquid pump calibration equation is:

$$Q_p = \frac{0.515 V_p + 0.0135}{1 + S + 0.29 S^2} \quad (3)$$

Free outflow rate equation is a non-linear equation as shown below:

$$q_o = 0.2383 h^{0.514} + 0.003 \quad (4)$$

These equations were used to build a closed loop simulation under LabVIEW 2014 environment in order to study the system behaviour when some faults may occur.

#### 4. Case Study

In this study, a PID controller under LabVIEW 2014 environment was used to preserve the desired liquid height and hence the required discharge. Liquid level and outlet valve opening have a direct impact on the free outflow rate. The specifications of the coupled tank apparatus CE 105 were used to build a closed loop simulation incorporated with the system elements' calibration equations (1- 4) and the parameters shown in Table 1. This simulation shows a response as similar as the test rig does at the same system parameters.

Table 1: The parameters were used for the simulation purpose

The liquid level set point	125 mm	
PID parameters	Proportional gain ( $K_c$ )	1
	Integral time ( $T_i$ , min)	0.01min
	Derivative time ( $T_i$ , min)	0 min
	Output high and low	10 volt and 0 volt respectively
Nominal pumping efficiency	100%	
Nominal outflow rate	According to the free outflow rate Equation (4)	

#### 5. Fault Modelling

As a result of ageing or long-term use, the system behaviour could change due to one or more abrupt and/ or incipient faults in some parts. The liquid level system can be divided into two main sides, a high-pressure and a low-pressure side.

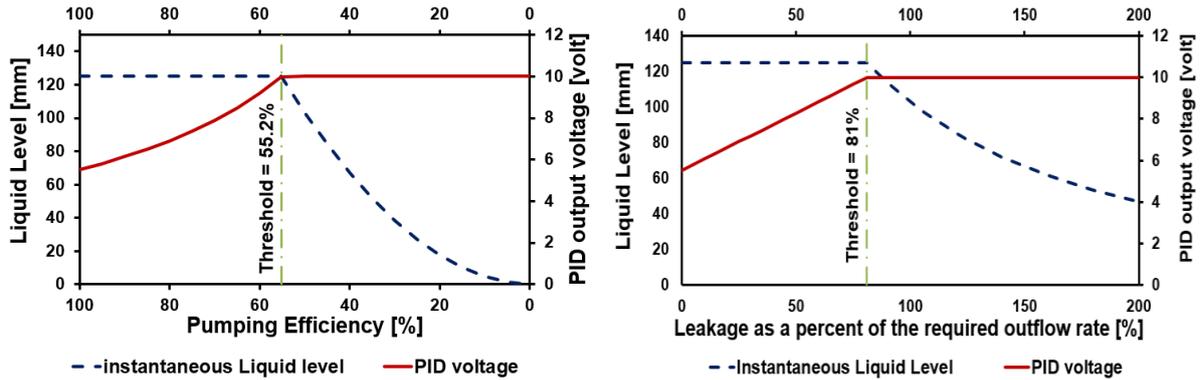
- A. The high-pressure side contains the system pump and the tank inlet pipe. Faults in this portion can be divided into two categories. A leakage in the tank inlet pipe is assumed to be an abrupt fault, this is the first category while the second is incipient faults that progress slowly with time. The latter includes a pump internal leakage or impeller wear, represented as a progressive degradation in the impeller area [1]; [3]. Bearings wear fault can be considered as an incipient fault progression in any type of bearings have been used, e.g. radial bearing or thrust bearing [3]. Degradation in the mechanical and/ or electrical efficiency has been represented in this research as a percentage of the nominal pumping efficiency.
- B. It is assumed that a fault in the low-pressure side, i.e. tank and drain line, occurs in two different ways. The first occurs when the outlet valve setting is abruptly changed to a new significant value and/ or a breakdown leads to massive leakage. Such fault usually settles at this value for a period of time. The second fault is assumed to be a time variant function and hence, the fault value has a

slow progression. For the purpose of this paper, this fault was represented as a percentage of the nominal outflow rate.

## 6. Results and Discussion

For the system parameters stated in the case study of a closed loop system and in presence of a PID controller, the liquid level will not be affected by a fault value if:

- The pumping efficiency reduces by up to 55.2%, as shown in Figure 3-a.
- The drainage from the tank increases by up to 81% from its designed value, as it can be seen in Figure 3-b.



a. Pumping efficiency and its impact on the liquid level and PID output voltage

b. Liquid leakage and its impact on the liquid level and PID output voltage

Figure 3: Impact of the pumping efficiency and liquid leakage on the PID voltage and liquid level

## 7. Conclusions

The PID controller hastens an increase in the voltage supplied to the pump in order to boost the liquid pumping rate to mask any reduction, caused by faults, in the required liquid level. This is true until the controller reaches its saturated high value or the maximum permissible pumping rate. When the controller reaches this threshold, the liquid level will drop by reason of an incremental fault value as shown in Figures 3-a and b. Each liquid level has its own threshold as a result of each fault.

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