Modelling of Level Process

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Abstract: Industries such as, textile, food processing, chemical and water treatment plants are part of our global development. The efficiency of processes used by them is always a matter of great importance. Efficiency can be greatly improved by obtaining an exact model of the process. This paper studies the two main classifications of model development – First-Principles Model and Empirical Model. First-Principles Model can be obtained with an understanding of the basic physics of the system. On the other hand, Empirical Models require only the input-output data and can thus factor in process non-linearity, disturbances and unexpected errors.

This paper utilizes the System Identification Toolbox in MATLAB for empirical model development. Models are developed for a single tank system, a classic SISO problem and for the two interacting tank system. Both systems are studied with respect to three operating points, each from a local linear region. The obtained models are validated with the real-time setup. They are satisfactory in their closeness to the real time process and hence deemed fit for use in control algorithms and other process manipulations.

Keywords : System identification, level process, first principle model, real time validation.

I. INTRODUCTION

Model applications can be found in the four major branches of process systems engineering, namely, design, estimation (prediction), control and monitoring. Central to all these applications is the use of models in simulations and predictions, which constitute the key incentives of model development. Simulations, by their computational nature, offer a cost and time-effective, safe alternative to experiments that are usually time-consuming, expensive and marked with safety issues. Model simulations are powerful ways of understanding processes, bringing about innovations and testing new designs and strategies. Petrochemical industries, hydrometallurgical industries, paper making industries, and water treatment industries pose large problems of nonlinearity and inseparable relationship between their dynamical parameters which does not provide the feasibility to obtain mathematical model of the complete system.

System identification offers the luxury to determine the approximate model for the system using the Input-Output data collected from the original system. The identified model can be used to tune the parameters of the controller and the resultant controller is used to control the original system. This technique can be used in any process and the only requirement is knowledge of the Input-Output dataset of the system.

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II. EXPERIMENTAL SETUP

All experiments have been conducted on a Multivariable Level Control Trainer, designed and manufactured by Apex Innovations. The setup consists of supply water tank with two variable speed positive displacement pumps for water circulation, five transparent process tanks fitted with level transmitters and flow dampers. The process signals from level transmitters are connected to Serial based duel loop PID controller. The controller is connected to computer through USB port communication. The process parameters are controlled through software and the output is fed to variable frequency drive used for the pumps. These units along with necessary piping are fitted on standalone support structure.

Fig. 1. Hardware Setup

III. FIRST PRINCIPLES MODELLING

A. Single Tank System

The single tank system setup consists of a cylindrical tank, an inlet pipe and an outlet pipe connected to a valve to offer resistance to the flow. The objective is to build a model that explains changes in level h(t) with respect to changes in inlet flow rate q_{in} (t).

From the law of conservation of mass:

$$\frac{dh}{dt} = q_{in} - q_{out} \quad (1)$$

$$\frac{d(A \times h)}{dt} = q_{in} - k\sqrt{h} \quad (2)$$

$$\frac{dh}{dt} = \frac{1}{A}(q_{in} - k\sqrt{h}) \quad (3)$$

Equation (3) is used to obtain a block diagram which is simulated using MATLAB Simulink 2016a.

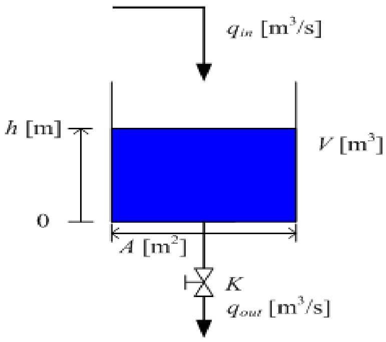

Fig. 2. Single Tank System

The Laplace transform of equation (4) is taken to obtain the transfer function of the system.

$$\frac{H(s)}{Q(s)} = \frac{R}{Ts+1}$$

(4)

Where $T = AR$

$$R = \frac{2\sqrt{h_s}}{k}$$

B. Two Tank Interacting System

The two tank interacting system poses a more complex process. It consists of two identical cylindrical tanks (Tank1 and Tank 2), a pump delivers the liquid flow to Tank 1. These two tanks are interconnected at the bottom through a manually controlled valve, R_1. The liquid flows out of Tank 2 through an outlet pipe connected to a valve R_2. Since the outlet flow of Tank 1 is channeled to Tank 2, the setup is ideal in order to understand within system interactions and dynamics.

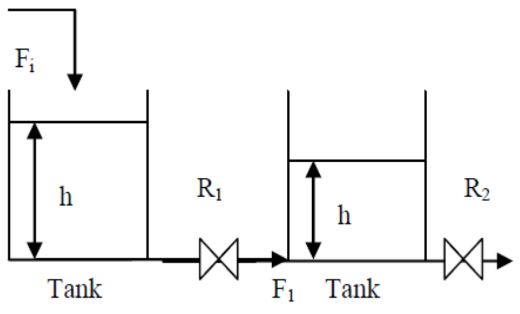

Fig. 3. Two Interacting Tank System

Variables Used:

Q_{in} (F_i) – inlet flow rate
Q_1 – outlet flow rate of Tank1
Q_{out} – outlet flow rate
h_1 – water level in the tank 1
h_2 – water level in the tank 2
A_2 – cross sectional area of Tank1
A_2 – cross sectional area of Tank2
k_1 – valve constant
k_2– valve constant

Using the Law of Conservation of Mass:

$$A_1 \frac{dh_1}{dt} = Q_{in} - Q_1 \quad (6)$$

$$A_2 \frac{dh_2}{dt} = Q_1 - Q_{out} \quad (7)$$

Where: $Q_1 = k_1\sqrt{h_1 - h_2}$

$$Q_{out} = k_2\sqrt{h_2}$$

$$\frac{dh_1}{dt} = \frac{1}{A_1}\{Q_{in} - k_1\sqrt{h_1 - h_2}\} \quad (8)$$

$$\frac{dh_2}{dt} = \frac{1}{A_2}\{k_1\sqrt{h_1 - h_2} - k_2\sqrt{h_2}\} \quad (9)$$

Equation (9) is used to obtain a block diagram which is simulated using MATLAB Simulink 2016a. The Laplace transform of equations (8) and (9) are taken to obtain the transfer function of the system.

$$(A_1 s + \frac{1}{R_1})H_1(s) = Q_{in}(s) - \frac{H_2(s)}{R_1}$$

(10)

$$(A_2 s + \frac{1}{R_1} + \frac{1}{R_2})H_2(s) = \frac{H_1(s)}{R_1}$$

(11)

Substitute equation (11) in (10)

$$\frac{H_2(s)}{Q_{in}(s)} = \frac{R_2}{T_1 T_2 s^2 + (A_1 R_2 + T_1 + T_2)s + 1}$$

(12)

Where

$$T_1 = A_1 R_1 \quad R_1 = \frac{dh_1}{dQ}$$

$$T_2 = A_2 R_2 \quad R_2 = \frac{dh_2}{dQ}$$

Thus the deterministic, first principles model has been obtained. This helps explain the physics of the system and helps predict system behavior. The obtained model is used as a guide when obtaining the empirical model through System Identification.

C. System Identification Method

System identification is the building a mathematical model of a dynamic system based on set of measured stimulus and response samples. A general procedure

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includes the following steps
1) Data Generation and Acquisition: Input and output variables about a particular operating point are obtained experimentally.
2) Model Development: Various models are simulated and the best fit % is calculated by comparing with the simulated model output.
3) Model Assessment: Model residuals, Transient response, Frequency response, Noise spectrum and Poles and Zeros plot of models with good fit% are utilized for further model analysis.
4) Model Validation: The identified system model is then hardware validated

D. Data Generation and Acquisition

Open loop response of single tank system and two tank system has been tabulated by allowing the liquid level to settle at various input levels. The response is used to identify local linear regions and select operating points for model development.

Table 1: Single Tank System

input (%)	h at steady state (mm)	Q_{out} (lph)	freq (Hz)
10	12.74	11.7	5.0
20	23.67	20.8	10.05
30	54.54	57.6	15.05
40	66.339	74.39	20.10
50	109.98	91.199	25.09
60	179.847	119.99	30.09
70	233.118	124.8	35
80	248.26	159.9	40
90	252.099	169.2	45
100	255.96	180	49.90

Table 2: Two Tank System

input (%)	h_1 at steady state (mm)	h_2 at steady state (mm)	Q_{out} (lph)	freq (Hz)
20	10.32	20.9	20.8	10.05
40	20.64	42	74.39	20.10
60	29.4	60	119.99	30.09
80	38	76.5	159.9	40
100	41.8	88	180	45

3 operating regions are identified from the graphical plot of input% vs. level of water. System identification is done about 3 operating points – 20%, 60% and 80%.

E. Model Development

The acquisitioned data is fed into the system identification toolbox for the generation of models.

Table 3: Generated Models at 20% input

Model Name	Description	Fit %
tf1	1 pole 0 zero Continuous	69.06
tf2	1 pole 1 zero Continuous	74.38
P1	1 pole Process model	69.06
pss1k	Order 1 K=estimate, predict PEM	54.77
pss1	Order 1 K=0, simulate PEM	95.27
P1Z	1 pole 1 zero Process model	74.38

Model ‘pss1’ is identified to have the best fit as its Model residuals; Transient response, Frequency response; Noise spectrum and Poles are Zeros plot fall with the 99% confidence limits. The Chirp signal response of the system identified model has been compared with the First-Principles model.

As both models display very similar responses, they have been deemed fit for further study. Models have been obtained for the single tank system at 60% and 80% input also and similarly for the two interacting tank system at 40%, 50% and 60% input.

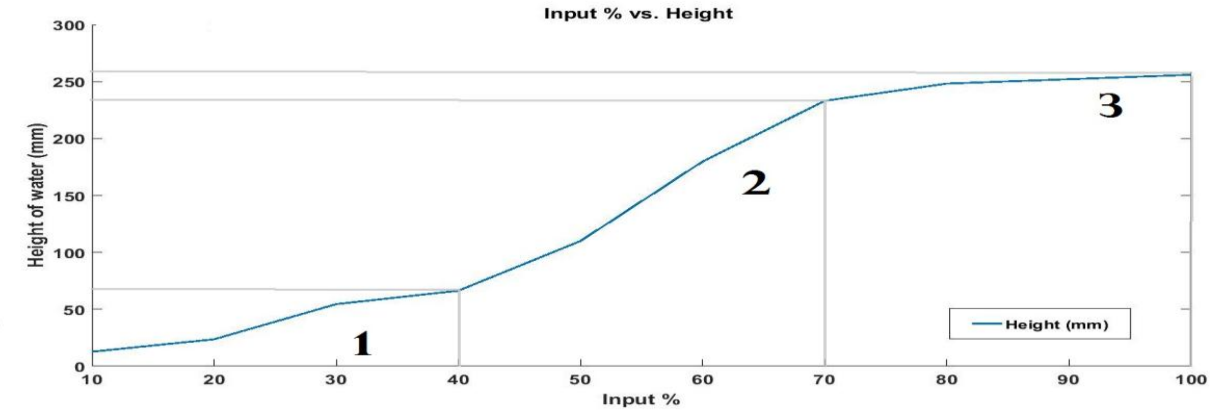


Fig. 4.Graphical plot of the input% vs. the liquid level in mm at steady state

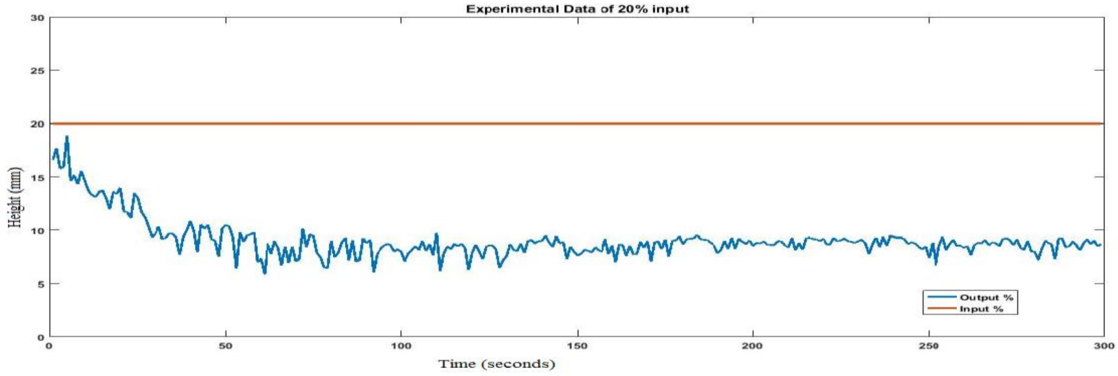


Fig. 5.Data for system identification at 20% input

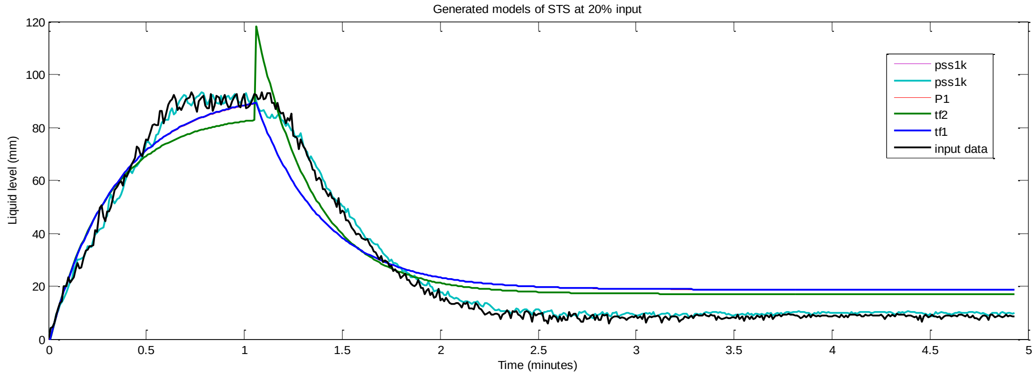
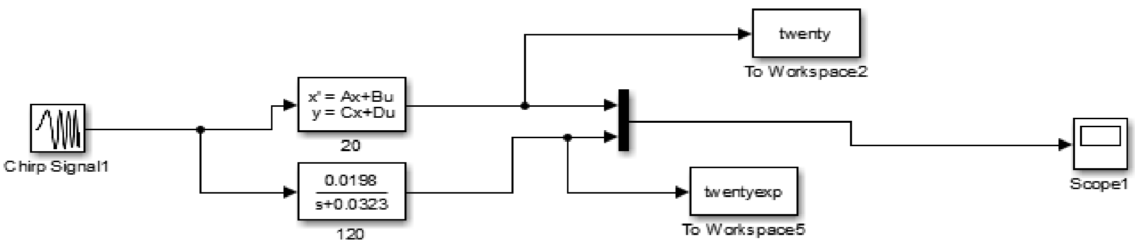
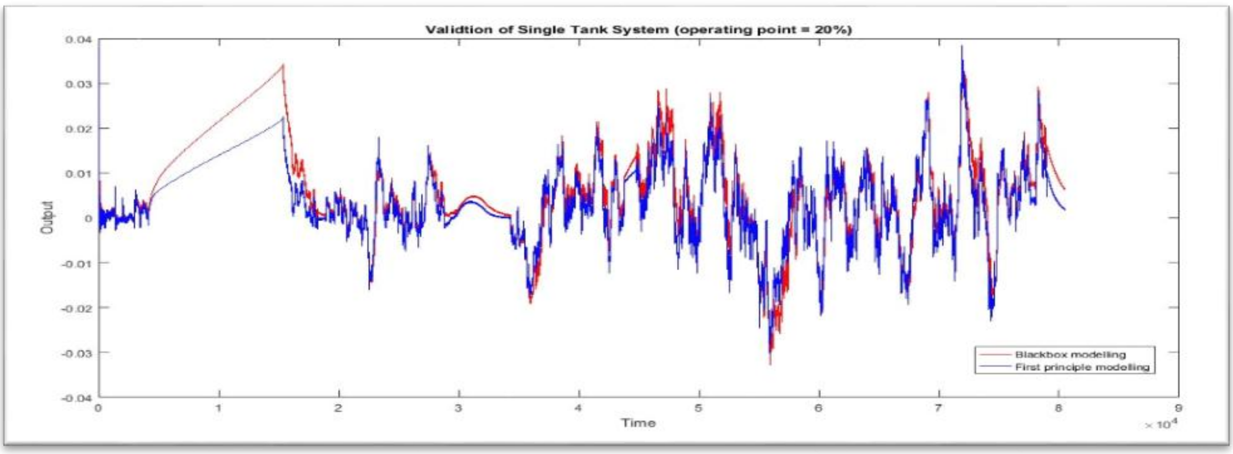


Fig. 6. Plot of output of generated models at 20% input



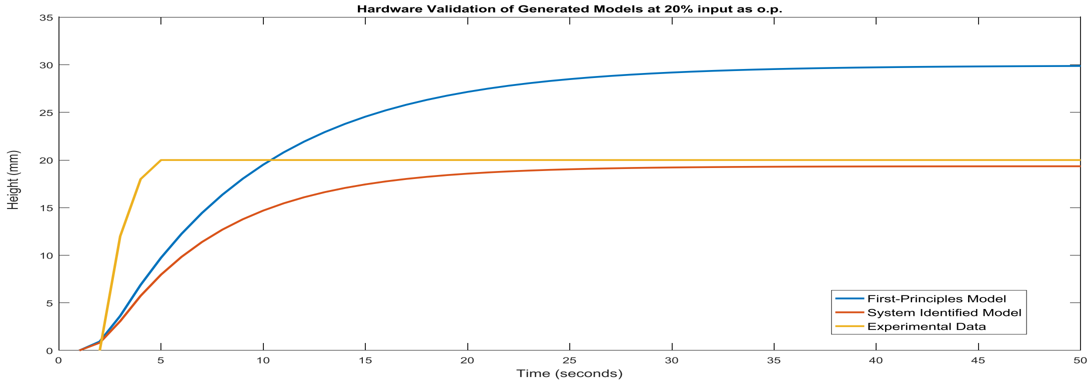


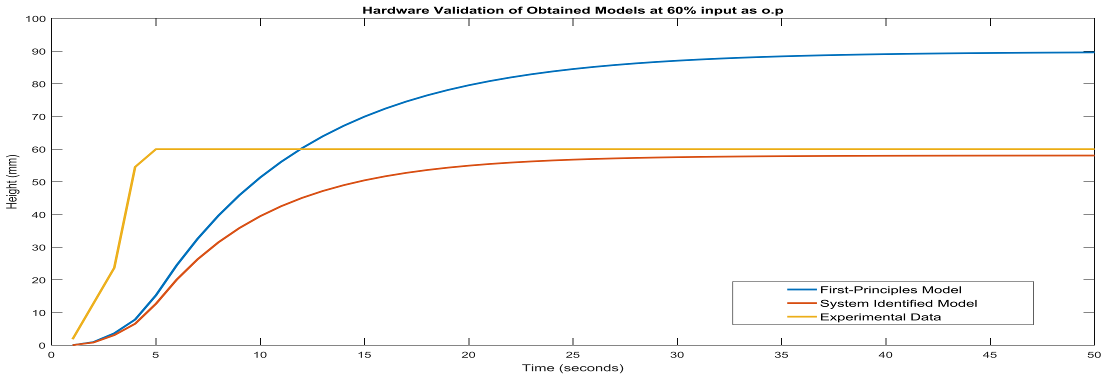
IV. RESULT

Table 4: Obtained First-Principles model and System Identified model at each operating point

Setup	Op. Point	First-Principles model	System Identified Model
Single Tank	20	$\frac{0.0198}{s+0.01323}$	$\frac{0.01729}{s+0.01787}$
	60	$\frac{0.22707}{s+0.012318}$	$\frac{0.01902}{S+0.01369}$
	80	$\frac{0.2271}{s+0.0109}$	$\frac{0.02194}{s+0.0171}$
Inter. Two Tank	40	$\frac{0.000792}{s^2+0.1194s+0.001584}$	$\frac{0.0008796}{s^2+0.07179+0.0006857}$
	50	$\frac{0.000792}{s^2+0.1194s+0.001584}$	$\frac{-0.000253s+0.002057}{s^2+0.09616s+0.002056}$
	60	$\frac{0.000792}{s^2+0.1194s+0.001584}$	$\frac{-0.005864s+0.005579}{s^2+0.2489s+0.00481}$

A. Hardware Validation





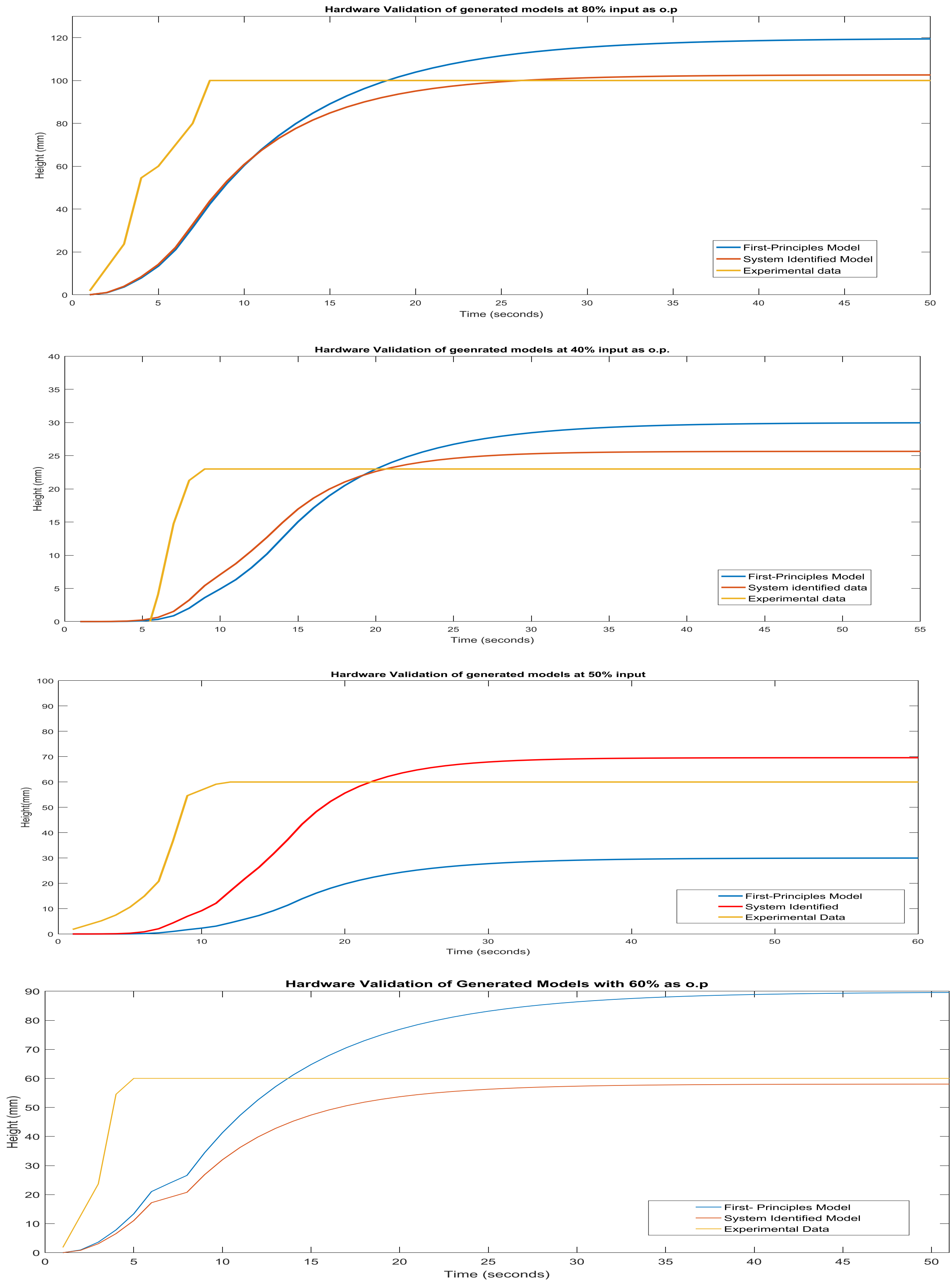


Fig. 7. Results of Hardware validation of Obtained Models for STS at 20%, 60% and 80% input, for TTIS at 40%, 50% and 60% input.

V. CONCLUSION

The obtained models are compared with real-time data to ascertain the better method of mathematical model attainment. In all 6 cases we observe that the System Identified model out-performs the First-Principles model due to its ability to factor in errors, non-linearities and process uncertainties. Thus the system identified model is deemed by virtue of its closeness to real-time data can now be used for the study of various controllers like PID, IMC, MPC etc.

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