IDENTIFICATION AND MODDELING OF WATER PHASE LEVEL INSIDE THREE-PHASE GRAVITY SEPARATOR SYSTEM

Title Page

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Abstract

This project is about the modelling, control and estimation of a three phase gravity separator. The work has been separated into more parts including, project specifications, modeling of the water phase level, experimentation done on the Laboratory setup, located at Aalborg University Esbjerg, and analysis of the obtained data in order to create a proper PI controller. The first part of the project included the study of first principles model in order to get a better understanding of the three phase gravity separator system. Once that has been done, the experiments have been designed and out of the five experiments two are presented and analyzed in this report. Once the data has been gathered and processed accordingly, the system could be identified and the PI controller created. Even though future work will be required, the project concluded with the attainment of two least square solutions capable of predicting the water phase level inside a three phase gravity separator. The associated prediction error of both solutions is in the same range with relatively "small" magnitude.

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Chapter I

1.1 Problem Formulation

1.1.1 Introduction

Top side processing is important part of oil and gas production. Due to the high complexity of the process, control over all systems involved is necessary. The focus of this project is evolving around the first stage of the separation process, carried out by a three-phase gravity separator system. Moreover, the interest is in providing stable operating conditions for a gravity separator system under the influence of slug inlet-flow. Lab setup of the three-phase gravity separator system connected with “hydrocyclon separator” stage, located at Aalborg University Esbjerg, will be used for this purpose. Developed model will be used for control purposes, with intention of investigating possible optimization regarding the water outlet-flow, which is one of the products of the separation process along with oil and gas.

The separation of the three phases is carried by a “Three phase gravity separator system”. Based on the function a separator can be classified as primary phase separator, test separator, high-pressure separator and low-pressure separators etc. To meet process requirement separators are designed in stages, where first stage separator is used as preliminary phase separation, while second and third stage are used for further treatment of each individual phase.

The system evaluated in this project is classified as first stage horizontal three-phase gravity separator and can be represented by the following illustration.

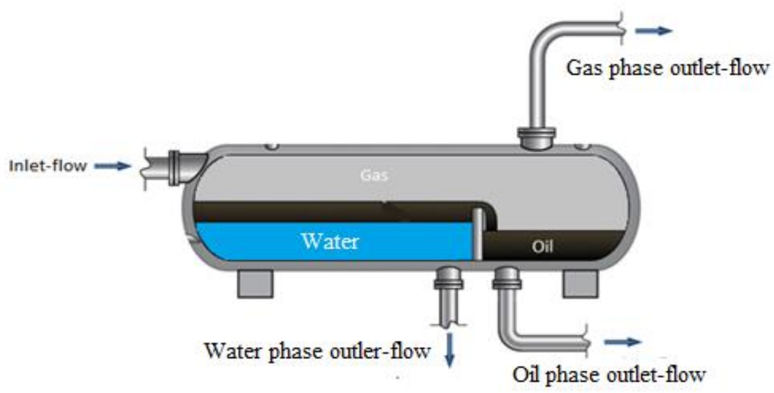

Fig.1.1.1 Three phase gravity separator
Source: http://goo.gl/fymPiv

The well stream defined as “Inlet-flow” in Fig.1 is entering into a separator tank’ where the velocity of the multi-phase stream reduces. Since oil is hydrophobic and lighter in viscosity from water, buoyancy is taking effect under gravitational influence resulting in the separation between water and oil phases. The separator vessel is dived into two control volumes by wire plate, where in time the formed oil layer is pushed and stored to a separate container as illustrated in Fig. 1. Furthermore, the free volume above the two liquid phases is occupied by the gas phase. Finally, the separated substances are drained from the separator vessel trough control valves.[10]

Since the considered system is first stage separator, the separation between oil and water is not optimal, and oil droplets will remain into the water phase. Subsequently, the water phase requires further treatment in order to be purified and returned to the original source.

Usually, the next stage of separation refers to as “hydrocyclon separator”. The “Water phase Outlet-flow” from Fig.1.1.1 is inputted to a cyclonic body, where the treatment of the “water phase outlet flow” continues under a vortex system, in which the outer vortex containing water is moving in the “underflow” direction and the inner vortex, containing oil droplets, is moving into the “overflow” direction as illustrated in the following Fig.1.1.2 [1].

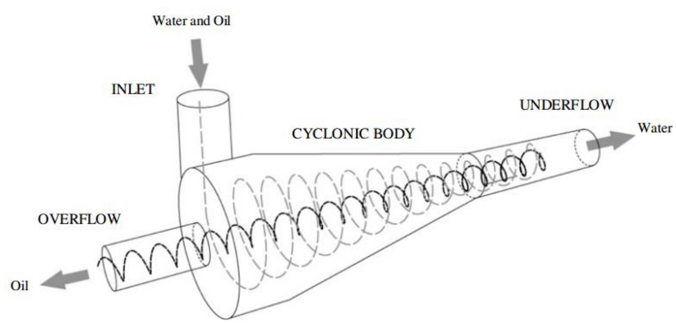

Fig.1.1.2 Hyrdocyclon separator

Sources: “Performance of a deoiling hydrocycl one during variable flow rates” [1]

Two main objectives are considered for this project. First one is to maintain the volume of the water phase level inside a separator vessel in permissible range, such that separation between oil and water is possible. Second objective is to increase the efficiency factor of the following “hydrocyclone separator” stage by providing, as steady as possible, water phase outlet flow from the considered three phase gravity separator system.

1.1.2 Problems occurring in separator systems under slug flow inlet flow conditions

Slug defines a multi-phase flow pattern occurring in pipelines, connecting a well located on the ocean (sea) bed with production platform (oilrig). The main reasons for occurrence of slug flow can be divide into two categories. First, given the ocean bed terrain and different elevations of the used pipelines can be a reason leading to formation of slugs. Second, a pipeline riser as illustrated in Fig.3, is use to direct the well fluid to the production facility.

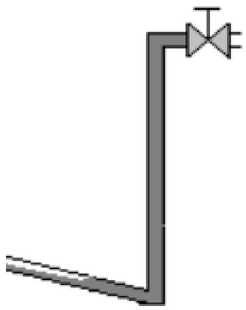

Fig.1.1.3 Pipeline riser with forming slug phenomenon
Sources: “The Slug Flow Problem in Oil Industry and Pi Level Control” [2]

Formation of slug starts by accumulating fluid in the bottom part of the pipeline riser, where after a given period of time, the well fluid will block the gas flow inside the pipeline, resulting in big continuous liquid slug. Under conditions, that pressure drop over the riser surpasses the hydrostatic head pressure of the liquid, formed slug will be “blown out” directly inside the separator system. Finally, after the slug leaves the riser, insufficiency of gas pressure will result in liquid fallback to the bottom of the riser, where accumulation of new slug starts all over again [4].

Slug flow is considered the most serious case of phenomenon causing instabilities influencing three -phase gravity separator systems. Under slug flow conditions, periods without any liquids or gas production are followed by big surges of inlet-flow entering the system, causing emergency shutdown of the processing station by triggering of alarm, indicating dangerous level of liquid inside all three-phase gravity separator systems. The results of such a shutdown are expensive and can reduce the oil production capacity.

Furthermore, due to the slug phenomenon occurring in three-phase gravity separator systems, the inlet-flow is oscillating in time. Which acts as disturbance causing oscillations of the water level inside the separator vessel and the water phase outlet flow. According to Husveg [1] the efficiency of a “hydrocyclone separator” is dependent on the amount of flow entering this stage of the separation process. It is pointed that the largest amount of efficiency in percentage is located in region between a minimum and maximum flow. Under condition of slug flow the water phase outlet-flow of a three-phase gravity separator system is oscillating and will result in less amount of flow, on average, entering the “hydrocyclone separator”. This implies that the efficiency factor of the following stage of the separation process will be reduced as shown in the following illustration.

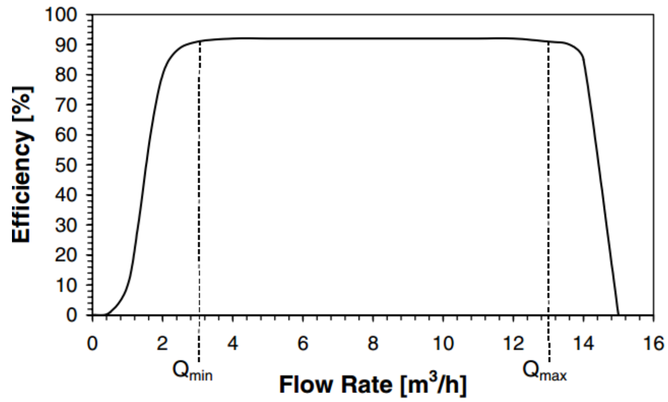

Fig.1.1.4 Hydrocyclone separator efficiency
Sources: “Performance of a deoiling hydrocycl one during variable flow rates” [1]

In summary, it can be stated that slug-flow is a critical problem occurring in offshore industry sector leading to high costs, losing production of oil and reduction in the efficiency of the next stage of separation.

1.1.3 Common control structures used in three phase gravity separator systems

Most common control strategy used to control the water level inside a three-phase gravity separator system is a PI controller. By applying such strategy, the main objective is to keep the water phase level at steady state. Where, under slug-flow this strategy will transfer all oscillations occurring in the inlet –flow of the system to the water phase outlet-flow, resulting in assurance that a three phase gravity separator will operate in safe conditions but reducing the efficiency of the following “hydrocyclon separator” stage [1] [2].

Second approach applied to control the level inside a three-phase gravity separator system is to let the water phase level deviate in permissible range (band). The separation process acting in the separator is flexible and will not be affected by controlled deviations of the water phase level. Two PI controllers are used in this type of control strategy. First, one is tuned to react faster on changes of the reference point and second one is tuned to react slower. Slow controller is used when the water phase level is in the region between a high and low water phase level set points. Faster controller is used when the level tends to move from the specified region. Using both controllers the occurring oscillations caused by the slug inlet-flow will be dampened, resulting in the reduction of water phase outlet-flow oscillations, which will also improve the efficiency of the next stage of separation [3].

However, even application of the two mentioned control strategies for controlling the water phase level inside a three-phase gravity separator system, PI controllers are suffering from limitations.

First limitation, which should be considered, is that a PI controller is bound by two tuning parameters. Where “P” term is introducing a steady state error, unless the proportional gain is large but with large gains issues with the stability of the considered system are arising. Furthermore, the integral term “I” of PI controller is compensating for the steady state error produced from the proportional term by bringing the error signal to zero in time. However, using “I” term will cause oscillations based on the fact that the integrated error will be the sum of all instantaneous errors over time, producing an accumulated offset that should have been corrected previously. Also due to “I” term in PI controller an integral windup can occur. Under condition that a positive change in the set point of a given system have occurred, the feedback controller can suppress the actuator’s maximum limit leading to the operation of the actuator on its limits, regardless of the system output.

1.2 Project requirements

The focus of this project is evolving around finding a solution to a non-conventional control problem with two main objectives evaluated under slug inlet-flow conditions. First objective is to maintain the water phase level of three-phase gravity separator system in a permissible range, such that the separation between oil and water is possible. Second objective is to reduce the oscillations of the water phase outlet-flow, caused by slug-flow entering the system.

The stated problem is complex and can be divided into several sub-problems with clear goals. First goal is to derive mathematical representation (model) of three-phase gravity separator system. Due to the higher order of degrees of freedom of such systems, this project will focus only on modelling the dynamics of water phase level inside a gravity separator tank. Second goal is to obtain reasonable model response, which will be evaluated against data obtained from the lab setup. Finally, a PI controller will be introduced to the open loop system. The main goal pursued with the final sub-problem is to stabilize the water phase level at given reference point and evaluate how this type of control structure will handle slug inlet flow, and what are the limitations and tradeoffs going along with the PID control structure.

Based on the three main goals for this project a set of requirements is formed to give clear definition of how every sub-problem can be solved. The project evolution will follow all requirements stated below:

1. Derivation of mathematical model of a three-phase gravity separator system based on empirical data.
2. Perform validation of a derived model against real life system response of the provided lab setup.
3. Application of PID controller for a closed loop system
4. Evaluation of a closed loop system

1.3 Project specifications

In order to fulfill all requirements defined in Section 2.1 clear specifications are defined. The set of specifications is divided into two main aspects. First set of specifications are describing the physical aspects of the considered system, followed by clear definition of what the model and control structure must satisfy in order to claim that the defined goals are achieved.

1.1.3.1. Three phase gravity separator lab setup physical specifications

The considered lab setup is a horizontal three-phase gravity separator with cylindrical body as illustrated on the following diagram.

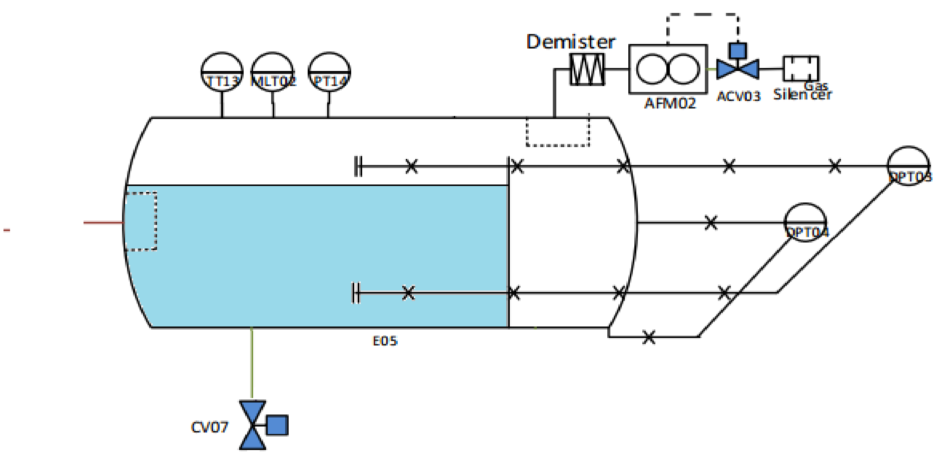

Fig.1.1.5. Three pase gravity separator diagram
Source: “Oil production simulator platform” [4]

The physical dimensions of the separator setup are defined in the following table.

Symbol	Definition	Value	Units
R	Separator tank radius	0.3	m
L	Separator tank length	1	m
V_t	Separator tank volume	0.2	m^3
Fin	Separator inlet flow	0.5-3.5	m^3/h
T_{trans}	Transient time of separator system at maximum inlet flow	3.025	sec

The key points of interest for this project can be observed in Fig.5. The water phase outlet valve "CV07" is the main control objective regarding the water phase level. The valve supports opening in the range from zero to hundred percent. The required time between fully closed and fully opened state is in the range between thirty to thirty five seconds. Sensor "MLT02" is responsible for measuring the current level of water inside the separator tank. "PT14" is measuring the gas pressure, accumulated in the free volume above the water phase. Sensor "DPT05" is measuring the differential pressure between top and bottom surfaces of the water phase. The derivation of a model describing the dynamics of the water phase level is achieved by combining the measurements of all mentioned sensors and taking into considerations the limitations of the actuator.

1.1.3.2. Project specifications

The following specifications are defined to form a basis for obtaining empirical model representing water phase level in a three phase gravity separator system.

1. Type: Linear black box model
2. Size: Polynomials of first degree.
3. Prize: Analytical and Recursive implementation of model parameter estimation.
4. Prediction error: $\varepsilon(t) \rightarrow 0 \; as \; t \rightarrow \; \infty \; and \; |\varepsilon(t)| < 10^{-3}$
5. Validation: Comparison between measured and predicted water phase level

Following the defined specification linear black box model derived from auto regressive extra input (ARX) model structure will be obtained. The considered model will be described by first order polynomials. Parameter estimator in the form of linear regression will be used to obtain values of the unknown parameters associated with the chosen model set. Least square criterion is considered as indication of model "quality", where the associated prediction error will satisfy the defined specification. Finally a graphical comparison between predicted and measured water phase level will be used to verify if the considered black box model is capable of representing the water phase level of the considered lab setup.

Furthermore, following the project requirements specifications for the closed loop system are defined, as two set of specifications associated with two different PI control structure as follow

1. "Fast" PI control structure:
    a. Rise time: 2-4 seconds
    b. Settling time: 5-10 seconds
    c. Overshoot: <15%

2. “Slow” PI control structure:
    a. Rise time: 30-35 seconds
    b. Settling time: 60-65 seconds
    c. Overshoot: <15%

Based on the two sets of specifications regarding the closed loop system, evaluation of the simulated system response under slug inlet flow operating conditions with an “aggressive” and “relaxed” PI control structure will be obtained. The results of the two closed loop systems will be evaluated and compared in order to obtain “general feeling” for the closed loop system, and how the water phase level will be influenced by a PI controller with two different characteristics.

Considering the defined specifications all project requirements should be fulfilled in the time frame of the project, providing a model describing the water phase level of the tree phase gravity separator lab setup, better understanding of the separation process and ideas regarding control and automation of the considered system.

Chapter II

Mathematical modeling of systems is essential part of control theory. By applying classical physics laws or utilizing empirical data, the dynamic characteristics of this system can be express in numerous ways. Model taking into consideration various static and dynamic parameters of a system will yield accurate approximation of the system. Furthermore, by evaluating the given model under different criteria, a controller can be derived and implemented in order to bring the system to steady state.

In order to fulfil the task of deriving a model describing the dynamic of the water phase level several key points are defined.

1. Derivation of model based on first principles of physics.
2. Experiments design.
3. Derivation of model based on empirical data.
4. Parameter estimation.

First key point in order to obtain reasonable model of gravity separator system is to derive an ordinary differential equation (ODE), describing how the water phase level is changing according to time. By applying such approach, a general overview of the considered system will be obtained. Valuable information regarding system inputs, outputs, static and dynamic parameters can be extract by evaluating the associated ODE, resulting in collecting prior knowledge for the system.

After obtaining a general "feeling" for the system, several carefully designed experiments are performed under different operating conditions. The main objective for this step is to extract as much as possible relevant information regarding the dynamic of the water phase level.

Based on the collected data from all experiments and using system identification procedures a model set can be selected. Furthermore, a criterion of fit for the given model is required in order to support a claim that the model will be able to satisfy the stated specifications in "Chapter I Section 3.2". Relaying on the selected model structure a parameter estimation is performed. Finally, after selecting a model structure and obtaining estimate of the model coefficients, validation of the simulated system response is performed by the comparison between measured and simulated water phase level.

2.1 Water phase level modeling

2.1.2 List of parameters and variables

Notation	Description	Units
$h(t)$	Water phase level	*m*
M	Water phase mass	*kg*
$Pg(t)$	Gas phase pressure	*bar*
C_v	Water phase outlet valve parameter	-
$F_{in}(t)$	Inlet flow water phase	m^3/h
$F_{out}(t)$	Outlet-flow water phase	m^3/h
$V(t)$	Gas pressure expansion factor	m^3
$P_w(t)$	Water phase pressure	*bar*
$P_{ow}(t)$	Water phase outlet-flow pressure	*bar*
ΔP	Differential pressure for water phase	*bar*
ρ	Water density	kg/m^3
ρ_i	Water inlet-flow density	kg/m^3
$f(u)$	Water phase valve opening function	*[0..1]*
A	Water phase cross-sections area	m^2
g	Gravity constant	m/s^2
$H_{1..4}$	System transfer function	-
$Val(t) = f(u)$	Water phase valve opening function	*[0..1]*
q	Forward shift operator	-
q^{-1}	Backward shift operator	-
θ	Vector of unknown parameters(general form[1])	-
a, b, c, d, k	Unknown parameters	-
$\varphi(t)$	Regressor vector (general form[1])	-
$V(\theta)$	Least square criterion function (general form[1])	-
$\varepsilon(t, \theta)$	Prediction error (general form[1])	-
$\hat{h}(t\|\theta)$	Water phase level predictor (general form[1])	-
$\hat{\theta}$	Unknown parameter estimator (general form[1])	-
$\lambda(t)$	Forgetfulness factor	-

[1] Notation asosiated directly with *a, b, c, d, k* are excluded instead general notation is provided

2.1.3 First principles model

Considering the fundamental law for conservation of masses, which stats that for any system closed for transfer of matter or energy the mass of the system must remain constant in time, as a system mass cannot change quantity if it is not added or removed. First principle model derives the change of water phase level according to time. [6] [7]

Using the idea of the fundamental mass balance equation, expressing the accumulation of mass in the system as the difference between the mass entering and leaving the system. Equation for the mass of water accumulated into the separator vessel can be obtain as follow.

$$\rho \frac{dM(t)}{dt} = \rho_i F_{in}(t) - \rho F_{out}(t) \tag{1}$$

Under the assumption that density of the liquid is not a function of concentration then all density terms from equation (1) can be neglected. Moreover, equation (1) is introduced in general form, which can relate to numerous systems. For the case of this study, the mass term *M(t)* is substituted with the volume of the water phase *V(t).*

Furthermore, in order to obtain equation expressing the water phase level, assumption of a linear relationship between the water phase volume and level exist as:

$$V(t) \approx ALh(t) \tag{2}$$

This assumption regarding the volume-level relationship is reasonable for the case of deviation of water phase volume in permissible range. By combining and substituting equation (1) and (2) an expression describing the water phase level deviation in time is obtained in equation (3)

$$\frac{dh(t)}{dt} = \frac{1}{AL}(F_{in} - F_{out}) \tag{3}$$

In agreement with the physical specifications of the three-phase gravity, separator system, stated in “Chapter I Section 3.1”, the outlet-flow leaving the separator vessel is passing through a controllable valve. Using a predefined valve equation of the following form (4) represents the water phase level of the system by expanding equation (3) [8] [6]

$$F_{out} = C_v f(u) \sqrt{\frac{\Delta P}{\rho g}} \tag{4}$$

Term C_v in equation (4) is combining the flow area of the valve orifice, the contraction coefficient and head loss coefficient in one. In origin, this term has been developed for turbulent flows but can be used for flows with kinetic viscosity below forty centistoke. In ninety percent of the cases, a liquid can be considered as a liquid with kinetic viscosity below the value of forty. The ΔP term originally is expanded as the difference between the inlet pressure and outlet pressure. An addition to these two terms is required in order to describe fully the physical relationship between water and gas phase. By introducing a term P_g, representing the accumulated gas pressure inside the separator vessel and adding it to the water phase pressure, an expression describing the total pressure exerted on the water phase during separation process is obtained. The difference between the total pressure and water phase outlet pressure is used to obtain the following equation for the differential pressure term ΔP [8].

$$\Delta P = (Pg(t) + P_w(t)) - P_{ow}(t) \tag{5}$$

Finally, by substituting equation (4) and (5) into equation (3), a mass balance equation describing the change of water phase level in time is expressed as the difference between the inlet flow entering the separator system and the outlet flow passing through a control valve as follows

.

$$\frac{dh(t)}{dt} = \frac{1}{AL} F_{in}(t) - \frac{1}{AL} C_v f(u) \sqrt{\frac{\left(P_g(t)+P_w(t)\right)-P_{ow}(t)}{\rho g}} \tag{6}$$

2.1.4 Summary

Using equation (6) as foundation for modeling the water phase of the considered system, several important statements can be concluded.

First, the considered system is defined as multiple-input single-output system (MISO). Second, the control input of interest is the flow characteristics function *f(u)*, representing the valve opening for the considered water phase outlet valve. However, several additional factors are influencing the system water-phase level. Gas, water and water outlet-flow pressure are considered as additional inputs to the system, which cannot be neglected. Finally, one more input to the system is defined. The inlet flow is considered as system disturbance due to the reason that only by disrupting the inlet flow entering the separator vessel, the system will be brought out from steady state.

Third, considering that all defined inputs for the system can be measured in real time on the available lab setup and by using, the prior knowledge for the system obtained from equation *(6)*, several experiments are designed to capture different dynamic responses of the considered system, as first step into a system identification procedure.

Finally, yet importantly by the derivation of first principle model clear definition of all factors influencing the water phase level is obtained. In addition, if new factors are considered in further stages of the project the first principle model provides predefined structure in which all new terms can be easily added in order to get better overview of the system

2.2 System identification

System identification is a scientific methodology for deriving mathematical models of dynamic systems based on observations. The following block diagram summarizes system identification procedure.

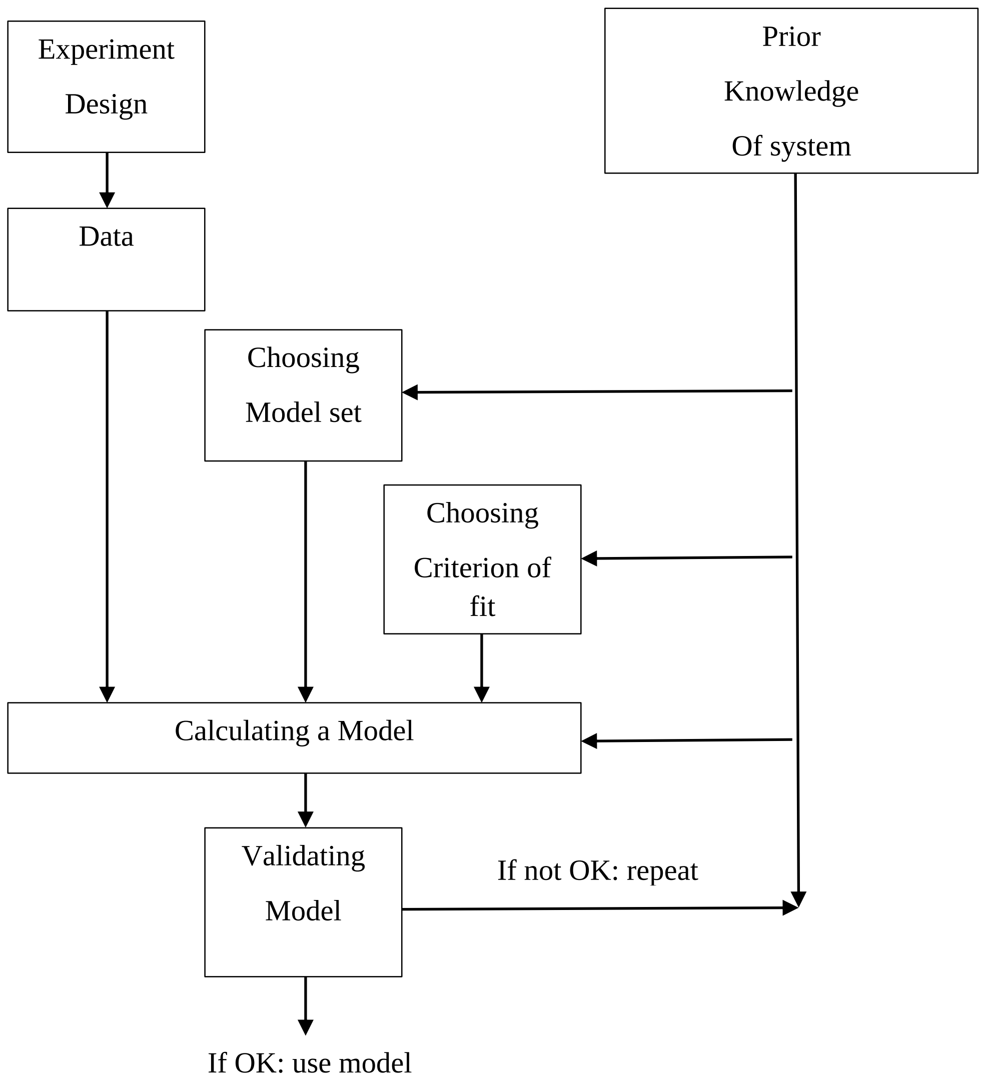

Fig.2.2.1 System Identification loop
Source: "System Identification Theory of the user Second edition" [5]

Every system identification procedure starts with prior knowledge of the system. The more information, regarding the considered system, is obtained in advance, the better the obtained experiments design will be. Second step in a system identification loop refers as Experiments design. This part is one of the most important steps. The experiments must be designed in such a manner that a maximum informative set of data can be obtained in order to capture all dynamics of the considered process or system. After all experiments are performed, data is collected and preprocessed in order to obtain sets of relevant information used to estimate system parameters based on a family of model sets, which the designer has chosen. After the data is ready and educated guess for the model set is made, a criterion of fit needs to be chosen. This criterion serves as an indicator how accurate the chosen model structure and estimated parameters will fit, compared to the measured system output. Finally, the model output can be calculated and validated against the measured output of the system. If the simulated and measured outputs are differing from each other in permissible range then the model is consider reasonable and applicable for control purposes. Otherwise, the system identification procedure should repeat itself until a model, satisfying the chosen criterion of fit is obtain [5].

2.2.2 Experiments design

In order to design experiments with intention of capturing dynamics of water phase level of three-phase gravity separator system, several questions are used to form the basis of an experiment.

1. What are the system's inputs and outputs?
2. What type of system inputs can be defined?
3. What type of signals can be selected for excitation of the system?
4. How many experiments are required?
5. Under what operating condition is an experiment performed?

Answers to the first and second question are a starting point for every design of an experiment. By using, the prior knowledge obtained in "Chapter II section 1.2", two types of system inputs are defined.

First type refers to manipulated input. This is the input, which is conserved with control of water phase level. In the physical perspective, this input is expressed as valve opening. By controlling how much water, is going out of the separator vessel the level itself can be manipulated. The second type of inputs to the system is referred to as measurable disturbances. Consideration of such signals rises from the derived first principle model. As it can be observed, several factors are influencing the change of water level in time. The water, gas, outlet-flow pressure and inlet-flow are assigned to the second category of inputs to the system. Since measurements of this, quantities are available on the considered lab. setup it is important to include them into the experiment design consideration. In conclusion, all input of the system, which must be put into consideration for this project, are listed below.

1. Manipulated(control) input $f(u)$
2. Measurable disturbance input $P_w(t)$
3. Measurable disturbance input $P_g(t)$
4. Measurable disturbance input $P_{ow}(t)$
5. Measurable disturbance input $F_{in}(t)$

After decision regarding which system inputs must be, considered for the system identification experiments design step, answer to third question is provided. In order to extract informative data by performing experiments on the considered lab setup the driving signal for every input must be carefully assigned.

In order to fulfill the requirement of obtaining a model representing the dynamics of the water phase level a persistent excitation of the control input is required. The choice for control signal is a “random binary signal (RBS)”. Since the valve opening is limited from zero to hundred presents or equivalently in scale from zero to one, a RBS is a sufficient choice for a signal, which can illustrate real life operation of a control valve. The considered measured disturbances cannot be manipulated. However, in order to introduce these quantities to the system several control signals are passed to the considered lab. setup. The first signal is a step function controlling a pump, which is responsible to supply the separator system with inlet-flow. For safety reasons the mentioned pump is driven with sixty percent power resulting in inlet flow in the range from zero to one cubic meter per hour.

Furthermore, in order to pressurize the system a gas release valve must be open. Two different input signals to the mentioned valve are considered for the experimental phase. The first choice is a step function, which will result in constant pressurized air stream entering the system. The second choice is a RBS resulting in simulation of varying pressure across the system during the execution of experiments.

The last consideration for signal required to run experiments on the three-phase gravity separator lab. setup is a step signal controlling a stream redirection valve. By adjusting, the position of the valve from open to close state alternation between two setup configurations is possible. The first configuration is a direct connection, in which the considered inlet-flow is directly entering the separator vessel. The second configuration is a riser configuration, in which the inlet-flow is passing thought system of bend and elevated pips resulting into slug inlet-flow entering the separator tank.

Proceeding further on in the experiment design, an answer to the fourth question is obtained. Several experiments under different operating conditions are conducted. Since all measurements are expected to be influence by transmission noise, the system is considered stochastic. Basis of ten trials per experiments are measure in order to obtain average values for every experiment. The sampling frequency for every measurement is a hundred hertz (Hz) in order to ensure that the Nyquist–Shannon theorem is satisfied and an aliasing problem will not occur.

Based on all considerations the final question can be answered. Five experiments are designed in total. Considering the project time limits, and specifications two experiments are selected for further investigation of the system.

2.2.2.1 Experiment One

The first experiment has the intention to illustrate simple dynamics of the system under scenario where constant stream of water is input into the separator vessel directly. The water-phase outlet valve is fully open at twenty seconds simulation time ensuring constant outlet-flow. Constant stream of air is injected into the system ensuring constant gas phase pressure inside the separator vessel. The duration of each trial of “Experiment one” is five minutes. The initial conditions of the system are as follow:

1. $h(t) \approx 0.26\ m$
2. $Pg(t) \approx 1.1\ bar$
3. $Pw(t) \approx\ 1.1\ bar$
4. $Pow(t) \approx\ 1.1\ bar$

The key point of interest is to obtain measurements of the following design variables.

1. Water phase level *h(t)*
2. Water phase pressure $P_w(t)$
3. Water phase outlet-flow pressure $P_{ow}(t)$
4. Gas phase pressure $P_g(t)$

Furthermore, two additional measurements regarding the water phase inlet and outlet flow are recorded during the execution of “Experiment one”. This data is used to analyze the influence of the inlet flow onto outlet flow with intention to illustrate a relationship between these two quantities.

In order to proceed within the system identification loop Fig.2.1 informative data regarding the considered measurements is collect and evaluate.

2.2.2.1.1 Data evaluation

Set of informative data is recorded during all ten trials of experiment considering the defined operating conditions. Based on measurements of the inlet and outlet flow, illustrated below, the following observations are made. First, the two flows are almost identical in transient response. At the starting time of the experiment, the inlet flow entering the system is approximately equal to the outlet-flow leaving the separator vessel, considered as equilibrium state. In order to bring the system out of equilibrium state the control valve is first fully closed followed by fully opened state, resulting in the observed drop around fifty seconds within experiment time. Furthermore, almost negligible oscillations occurring in the inlet flow around one hundred and fifty seconds experimental time, are amplified and transferred in the outlet-flow, indicating sensitive relationship between the two flows. Finally, a time constant regarding the inlet flow response is obtained in the range between three and three and a half minutes.

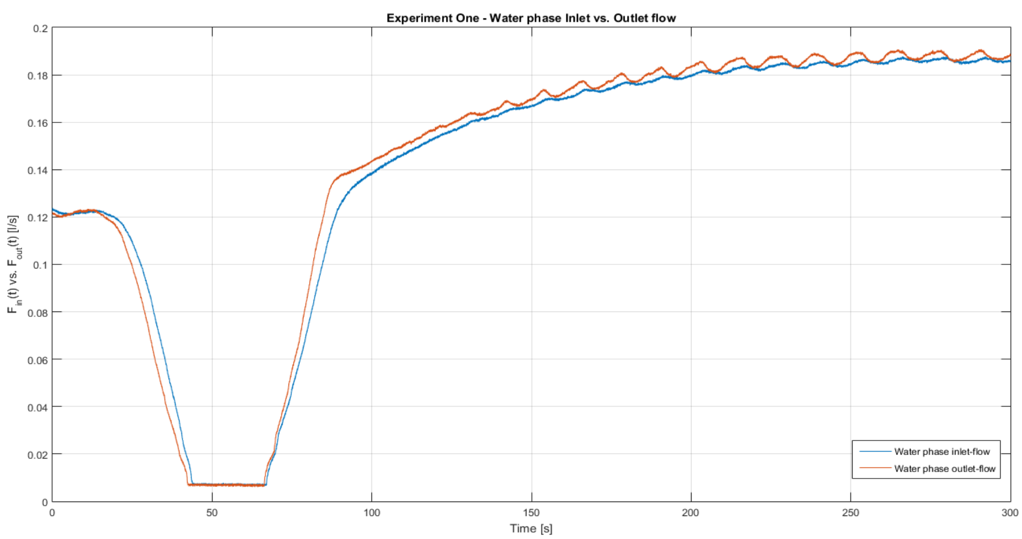

Fig.2.1.1.1 Water phase Inlet vs. Outlet flow

The set of informative data is extended by obtaining measurements of all internal factors influencing the water phase level. The transient responses of water, gas and water outlet-flow pressure are present in Fig.2.1.1.2 . The transient response of the water and gas pressure are almost identical. As the control valve is beginning to close down, the water and gas pressure starts to increase gradually to a point where the valve is opened, leading to an occurrence of a pressure drop. Slightly greater drop is observed in the gas phase pressure, which is expected, as the accumulated gas phase pressure inside the separator vessel is influenced, not only by the valve opening but also by the water phase volume. Furthermore, it is observed that the water phase pressure along with the water phase outlet-flow pressure are influenced only by the transient response of the control valve. From Fig.2.1.1.2 also can be observed that the time constant associated with the three measured quantities is approximately three minutes.

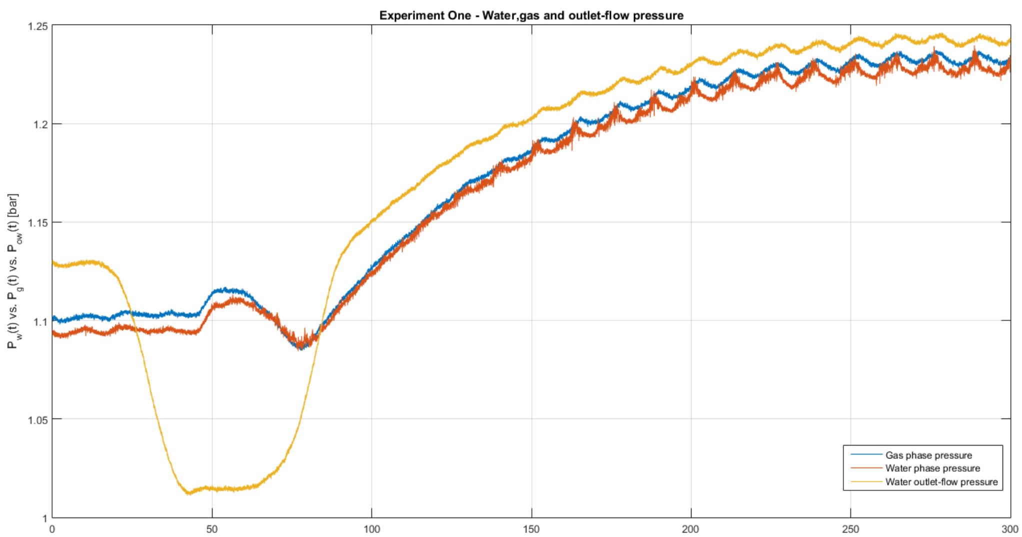

Fig.2.1.1.2 Measurable disturbances

Finally yet importantly, measurements of the water phase level are obtained and illustrated on Fig.2.1.1.3. As expected the water level is decreasing at the start of the experiment to a point where the control valve is fully closed. Furthermore, it is observed that the next steady state of the water phase level is occurring in the end of the experiment, from which follows that the time constant of the water phase level is approximately three minutes and fifteen seconds. In addition, oscillations occurring in the inlet-flow entering the systems are also amplified and transferred into the water phase level, as midpoint interaction, between inlet and outlet flows.

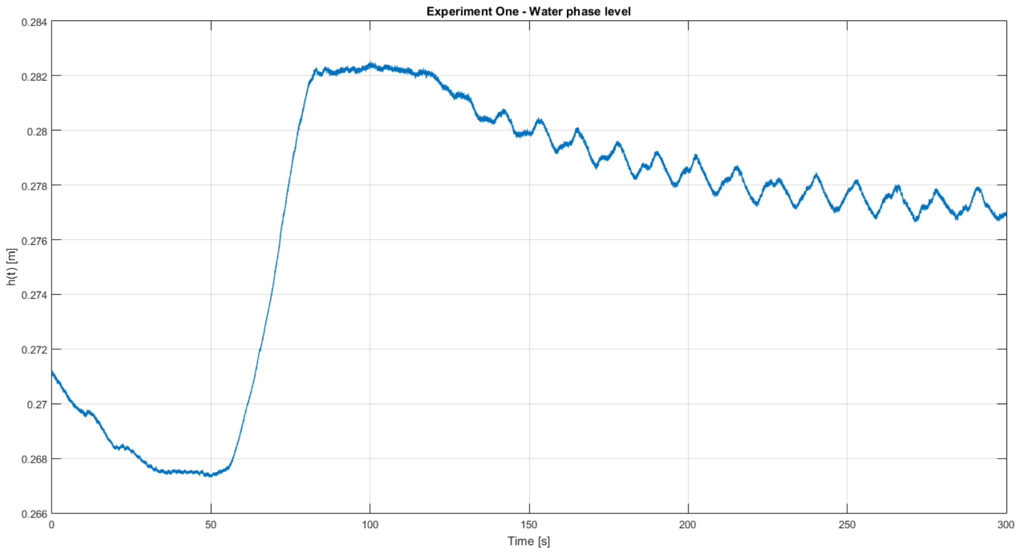

Fig.2.1.1.2 Water phase level

2.2.2.1.2 Summary

Several key points are obtained from “Experiment one”. Evaluating the system running from one steady state to another using step input signals for all manipulated inputs of the lab setup, a time constant for every design variable is defined as follow.

1. Water phase level – 3.15 min.
2. Gas phase pressure - 2.5 min.
3. Water phase pressure – 3 min.
4. Water phase outlet-flow pressure – 3 min.

All time constants are obtained after the considered control valve is transitioning to fully open state executed after fifty seconds within experiment time. It is found that the required time on average for the considered open loop system to react on step input and reach new steady state is three minutes and ten seconds.

During the evaluation of the recorded data from “Experiment one”, it was found that the obtained data from the sensor responsible for measuring the water phase level is unreliable. However, additional measurements regarding the water phase differential pressure were recorded during the execution of “Experiment one”, providing enough information to obtain a transient response of the water phase level.

Finally based on the observed data, it is concluded that the water phase level and outlet-flow are sensible to oscillations occurring in the inlet-flow entering the separator, implying that potential slug flow can heavily influence the system, and further evaluation of the system is required in order to meet the project requirements.

2.2.2.2 Experiment Two

The second experiment is designed with intention to capture the dynamic of the system under slug inlet –flow. To achieve this goal the lab setup is used in riser configuration. The produced stream of water is passing through the system of bended pipes to a point where the inlet flow is elevated through a riser. Slugs are accumulated in the bottom part of the riser and at given point in time are released into the system resulting in deviations of the inlet-flow. Furthermore, in order to emulate real life operating conditions one transition between open and closed state of the water phase valve is not sufficient, instead RBS is used to drive the valve. In addition, the pressurized gas injected into the system is also varying with time.

Ten trials are recorded to form foundation for "Experiment two". Each trial is with duration of eight and a half minutes. The initial conditions of the system are presented below.

1. $h(t) \approx 0.26\ m$
2. $Pg(t) \approx 1.3\ bar$
3. $Pw(t) \approx\ 1.0\ bar$
4. $Pow(t) \approx\ 1.0\ bar$

Same design variables of interest from "Experiment one" are measured and recorded during the second experiment. The following results are presented in the section below.

2.2.2.2.1 Data evaluation

The inlet and outlet flow have different transient response compared to the obtained data from "Experiment one". The inlet flow entering the system in deviating in time significantly. Through observations and considering the chosen speed of the produced inlet flow, is concluded that slugs starts to occur after hundred seconds within experiment time. Fig. 2.2.2.2.1.1 illustrates the influence of slug inlet flow to the outlet-flow of the water phase, confirming that slug flow have direct and heavy influence over the water phase outlet flow. In addition, is observed that under slug inlet flow the system is not reaching new steady state during experimental time, proving that under such conditions a system that is defined as stable by presumption is no longer able to reach steady state.

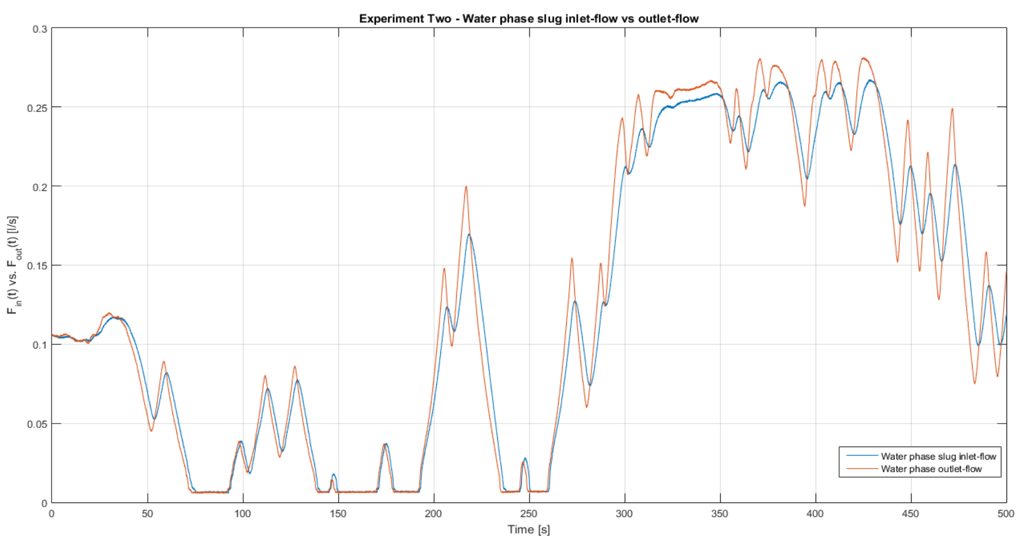

Fig.2.2.2.2.1.1.Slug inlet-flow vs. water phase outlet-flow

Figure 2.2.2.2.1.2 is illustrating the three defined measurable disturbances influencing the system. Considering the defined operating conditions, several important observations are obtained. First, the water phase pressure is tending to increase linearly in comparison with gas and water phase outlet flow pressure. The accumulated gas phase pressure is deviating in time but on overall scale tends to increase in the same manner as the water phase pressure. Since the water phase outlet flow pressure is influenced by the two other measurable disturbances along with the considered control valve, the obtained transient response is heavily oscillating during the experimental time.

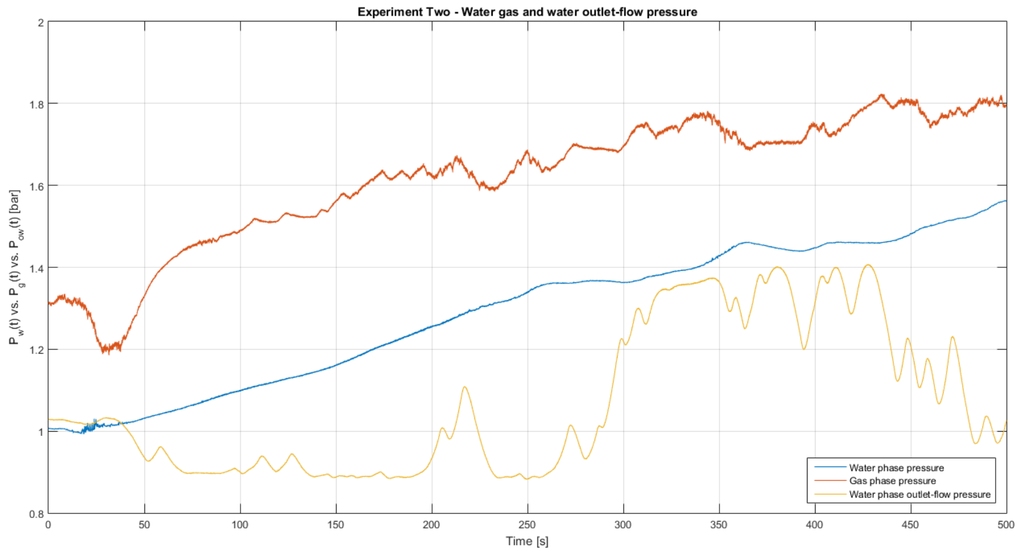

Fig. 2.2.2.2.1.2 Measurable disturbances

Considering that a fault is found in the sensor responsible for measuring the water phase level during the first experiment, the transient response of the level for the second experiment is obtained thought scaling the output of the pressure difference sensor. The obtained measurement is presented in Fig. 2.2.2.2.1.3. First, it is observed that against reasonably slow slug inlet-flow entering the system the occurring oscillations of the inlet-flow are almost undetectable in the water phase level. However, the outlet flow is clearly indicating the presents of such oscillations and deviations of the water phase level at time instance around eighteen, fourth five and similar are related to the inlet-flow oscillations. Considering that the control valve is in open state in the start of every trial of “Experiment two” and as applying RBS as control input, the observed transition of the valve is described as stepwise movement from fully open to fully closed state explaining the accumulation of water inside the separator vessel.

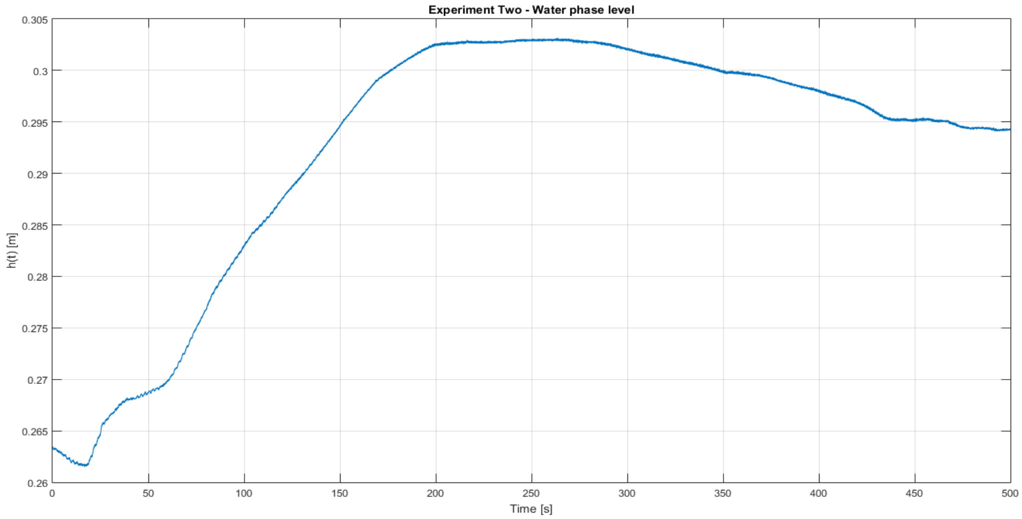

Fig. 2.2.2.2.1.3Water phase level

2.2.2.2.2 Summary

As a continuation of the system evaluation “Experiment Two” have provided additional information regarding the system. “Experiment Two” is taking into consideration operating conditions, which are providing better description of real life working conditions of a three-phase gravity separator system.

Furthermore, the experiment is held in laboratory environment, considering the safety and physical limitations of the lab setup, collection of data in the lowered band of inlet-flows allowed to enter the system is obtained, concluding that more experiments in the different bands should be designed.

Moreover, by confirming .with “Experiment two” , the stated relationship from the first experiment a conclusion that slug inlet flow can be considered a factor reducing the efficiency of a “hydrocyclone separator”.

Finally yet importantly a data set is obtained during “Experiment two”, providing the required data in order to proceed within the system identification procedure.

2.2.3 Conclusions over Experiments design

Experiments design is one of the most challenging tasks in a system identification procedure. Careful planning and enormous amount of factors must be considered in order to obtain relevant data set. It is time-consuming phase, and errors must be brought to the minimum. From personal observations, if the experiments are designed, executed and evaluated sequentially, a recursive way of experiments design is achieved, allowing the obtained knowledge from every previous experiment to be used in the design of each following one. In addition, is concluded that a possibility of sensor fault is always to be considered, and good practice is to ensure a backup sensor, from which the key measurements can be obtained directly or thought mathematical manipulations.

As mentioned in “Chapter II Section 2.1”, five experiments in total were designed. Every experiment consists of ten consecutive trials, recording measurements of all design variables. The average of every measurement is used to obtain final data set associated with each experiment. In order to fit within the time limits of the project only two out of the five designed experiments are presented and evaluated in depth.

The first experiment is proven a success. The time constant associate with the different design variables are obtained, along with prior knowledge of the lab. setup, and valuable information regarding relationship between water phase level, inlet and outlet flow is concluded.

The second selected experiment is chosen to evaluate the system under slug flow conditions. Evaluating and comparing the obtained data set provides enough confidence to state that the obtained information from “Experiment two” will be used to estimate parameters and obtain a model describing the water phase level of a three-phase gravity separator system. Reasonable recommendation for future work is to design at least two more experiments considering worst-case scenario of slug inlet-flow entering the system.

Finally yet importantly considering the derived mass balance model, the relationship between water, gas and water phase outlet pressure is mathematically represented by subtraction and addition. However, during experimentation, nothing of the observed data indicates such a relationship; therefor further investigation of possible relationship function can be considered

2.2.4 System model and Criterion of fit

Considering the data set from "Experiment Two" and the derived first principle model a general form of linear time invariant system is chosen to represents the dynamics of the water phase level.

$$h(t) = H_1(q)Val(t) + H_2(q)P_w(t) + H_3(q)P_g(t) + H_4(q)P_{ow}(t) \tag{2.1}$$

A particular model corresponds to specification of functions *H* in (2.1) It is not possible to determine any coefficients associate with the two functions a priori, introduction of a parameter vector θ and expansion of the considered model is required, resulting in a set of models as illustrated in equation (2.2)

$$h(t) = H_1(q,\theta\,)Val(t) + H_2(q,\theta)P_w(t) + H_3(q,\theta)P_g(t) + H_4(q,\theta)P_{ow}(t) \tag{2.2}$$

One of most common way to parameterize the functions *H* is to represent them as rational functions with unknown parameters θ being numerator and enumerator coefficients of a transfer function. This is achieved by expressing the considered system inputs-output relationship as the following linear difference equation [5].

$$\begin{aligned} h(t) + a_1 h(t-1) + \cdots + a_{n_a} h(t-n_a) \\ = b_1 Val(t) + \cdots + b_{n_b} Val(t-n_b) + c_1 P_w(t-1) + \cdots + c_{n_c} P_w(t-n_c) \\ + d_1 P_g(t-1) + \cdots + d_{n_d} P_g(t-n_d) + k_1 P_{ow}(t-1) + \cdots + k_{n_k} P(t-n_k) \end{aligned} \tag{2.3}$$

Equation *(2.3)* is also referred to as auto-regressive extra-input (ARX) model structure, defining the current water phase level as function of known values of previous input and output measurements. Following equation (2.3) definition of the unknown parameter vector θ as follow [5].

$$\theta = \left[[a_1 \ldots a_{n_a}]\ [b_1 \ldots . b_{n_b}]\ [c_1 \ldots c_{n_c}]\ [d_1 \ldots d_{n_d}]\ [k_1 \ldots k_{n_k}]\right]^T \tag{2.4}$$

Proceeding further five polynomials are defined based on the chosen ARX models structure.(2.3).

$$A(q) = 1 + a_1 q^{-1} + \cdots + a_{n_a} q^{-n_a} \tag{2.5.a}$$

$$B(q) = b_1 q^{-1} + \cdots + b_{n_b} q^{-n_b} \tag{2.5.b}$$

$$C(q) = c_1 q^{-1} + \cdots + c_{n_c} q^{-n_c} \tag{2.5.c}$$

$$D(q) = d_1 q^{-1} + \cdots + d_{n_d} q^{-n_d} \tag{2.5.d}$$

$$K(q) = k_1 q^{-1} + \cdots + k_{n_k} q^{-n_k} \tag{2.5.e}$$

Considering that the desired water phase level is expressed as linear combination between the four considered inputs, predictors of the water phase level with respect to each considered input is derived as follow

$$\hat{h}(t|\theta) = B(q)Val(t) + [1 - A(q)]h(t) \tag{2.6.a}$$

$$\hat{h}(t|\theta) = C(q)P_w(t) + [1 - A(q)]h(t) \tag{2.6.b}$$

$$\hat{h}(t|\theta) = D(q)P_g(t) + [1 - A(q)]h(t) \tag{2.6.c}$$

$$\hat{h}(t|\theta) = K(q)P_{ow}(t) + [1 - A(q)]h(t) \tag{2.6.d}$$

First important observation is that all derived predictors are expressed only by previous values of the considered variables of interest. Furthermore, every predictor defined is responsible to provide estimates only associated with a, b, c, d or k parameters defined in equation (2.3). By defining four regression vectors containing data regarding previous water phase level and previous specific input as follow:

$$\varphi_v(t) = [-h(t-1) \ldots - h(t-n_a) \;\; Val(t-1) \ldots Val(t-n_b)]^T \tag{2.7.a}$$

$$\varphi_w(t) = [-h(t-1) \ldots - h(t-n_a) \;\; P_w(t-1) \ldots P_w(t-n_c)]^T \tag{2.7.b}$$

$$\varphi_g(t) = \left[-h(t-1) \ldots - h(t-n_a) \;\; P_g(t-1) \ldots P_g(t-n_d)\right]^T \tag{2.7.c}$$

$$\varphi_{ow}(t) = [-h(t-1) \ldots - h(t-n_a) \;\; P_{ow}(t-1) \ldots P_{ow}(t-n_k)]^T \tag{2.7.d}$$

The derived predictors of the water phase level associated with each independent input defined in equation (2.6) are expressed as scalar product between the known data defined in (2.7) and the associate unknown parameters θ_i $i = a, b, c, d, k$ by the following relationship also referred as linear regression model.

$$\hat{h}(t|\theta_b) = \varphi_v(t)^T \theta_b \tag{2.8.a}$$

$$\hat{h}(t|\theta_c) = \varphi_w(t)^T \theta_c \tag{2.8.b}$$

$$\hat{h}(t|\theta_d) = \varphi_g(t)^T \theta_d \tag{2.8.c}$$

$$\hat{h}(t|\theta_k) = \varphi_{ow}(t)^T \theta_k \tag{2.8.d}$$

After all predictors are defined, a criterion is chosen, in order to quantify the difference between measured and calculated water phase level, providing enough information to justify the choice of a particular model from the defined in equation (2.2) set of models.

2.2.4.1 Least square criterion of fit

From the four predictors in equation (2.8), a prediction error function, associated with each predictor, expressed in (2.9) as the difference between the measured and predicted values representing the water phase level is chosen to quantify if a given set of models is satisfying the project specifications.

$$\varepsilon_b(t,\theta_b) = h(t) - \varphi_v^T(t)\theta_b \tag{2.9.a}$$

$$\varepsilon_c(t,\theta_c) = h(t) - \varphi_w^T(t)\theta_c \tag{2.9.b}$$

$$\varepsilon_d(t,\theta_d) = h(t) - \varphi_g^T(t)\theta_d \tag{2.9.c}$$

$$\varepsilon_k(t,\theta_k) = h(t) - \varphi_{ow}^T(t)\theta_k \tag{2.9.d}$$

From stochastic framework point of view, the defined prediction errors in (2.9) are minimized by the conditional expectations of the water phase level and the associate regression vector, resulting in the minimum variance between measured and predicted water phase level. However, a clear a priori information about the relationship between the water phase level and the regressor vector is not obtained from the considered data set, instead using the collected data as a sample variance function as in (3.0) associated with each individual prediction error is used. Due to the fact that the sum of squares between the difference of observed and calculated quantities represented by the sample variance must be minimum equation (3.0) is used as linear least square criterion regardless that the system is considered deterministic. [5]

$$V_b(\theta_b) = \frac{1}{N}\sum_{t=1}^{N}(h(t) - \varphi_v^T(t)\theta_b)^2 \tag{3.0.a}$$

$$V_c(\theta_c) = \frac{1}{N}\sum_{t=1}^{N}(h(t) - \varphi_w^T(t)\theta_c)^2 \tag{3.0.b}$$

$$V_d(\theta_d) = \frac{1}{N}\sum_{t=1}^{N}\left(h(t) - \varphi_g^T(t)\theta_d\right)^2 \tag{3.0.c}$$

$$V_k(\theta_k) = \frac{1}{N}\sum_{t=1}^{N}(h(t) - \varphi_{ow}^T(t)\theta_k)^2 \tag{3.0.d}$$

After specifying the criterion functions two solutions regarding all parameter θ which minimize the prediction error (2.9) are considered in order to obtain simulation of the water phase level.

2.2.4.2 Analytical Least square Solution

Using the defined least square criterion as a starting point, values for the unknown parameters can be obtained analytically by solving the following equations.

$$\hat{\theta}_b = \left[\frac{1}{N}\sum_{t=1}^{N} \varphi_v(t)\varphi_v^T(t)\right]^{-1} \frac{1}{N}\sum_{t=1}^{N} \varphi_v(t)h(t) \tag{3.1.a}$$

$$\hat{\theta}_c = \left[\frac{1}{N}\sum_{t=1}^{N} \varphi_w(t)\varphi_w^T(t)\right]^{-1} \frac{1}{N}\sum_{t=1}^{N} \varphi_w(t)h(t) \tag{3.1.b}$$

$$\hat{\theta}_d = \left[\frac{1}{N}\sum_{t=1}^{N} \varphi_g(t)\varphi_g^T(t)\right]^{-1} \frac{1}{N}\sum_{t=1}^{N} \varphi_g(t)h(t) \tag{3.1.c}$$

$$\hat{\theta}_k = \left[\frac{1}{N}\sum_{t=1}^{N} \varphi_{ow}(t)\varphi_{ow}^T(t)\right]^{-1} \frac{1}{N}\sum_{t=1}^{N} \varphi_{ow}(t)h(t) \tag{3.1.d}$$

Using equation (3.1) to estimate values for the unknown parameters yields for the global minimum of the criterion functions defined in (3.0), results in the minimization of the prediction error of the model. First important condition to obtain results is that the formed matrix on the left in equation (3.1) is invertible. Second condition taken into consideration is that the measurement noise has normal distribution, with zero mean, resulting in prediction of the water phase level independent from the measurement noise. Finally, it is assumed that the input sequences are also independent from the measurement noise [5].

Based on the derived parameter estimators and the chosen data set a model predicting the water phase level inside the three phase gravity separator is obtained. Considering that the chosen data set is influenced by measurement noise, a low-pass filter with pass band of 1-15 Hz is applied, to extract as much as possible informative data from the chosen data set. After the filtration of the measurement noise, it is concluded that the data set containing 50000 samples for each measurement will demand great computational power to obtain solutions to (3.1). By splitting the data into four windows of 10000 samples, the computational power is reduced significantly, allowing the estimation procedure to be performed. The following results are obtained.

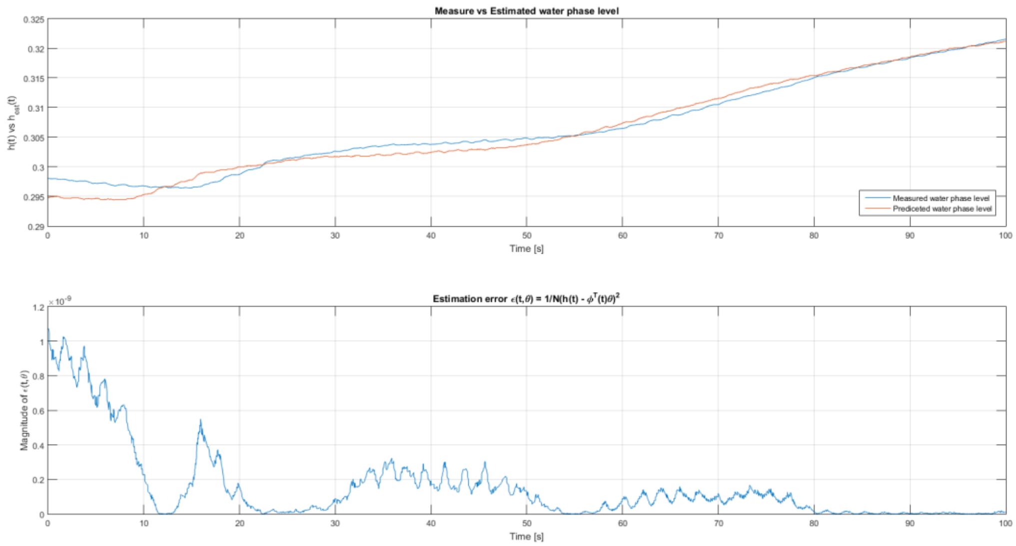

Fig.2.2.4.2.1 Window one Measured vs Estimated water phase level

The predicted water phase level associated with the first window of data is following the measured level with slight offset. However, after the point of eighty seconds it is observed that the error is converging close to zero, indicating that the prediction error is minimized successfully. In spite of that, one window is not enough to justify that the method is working correctly. The following graph illustrates the results associated with the second window of data.

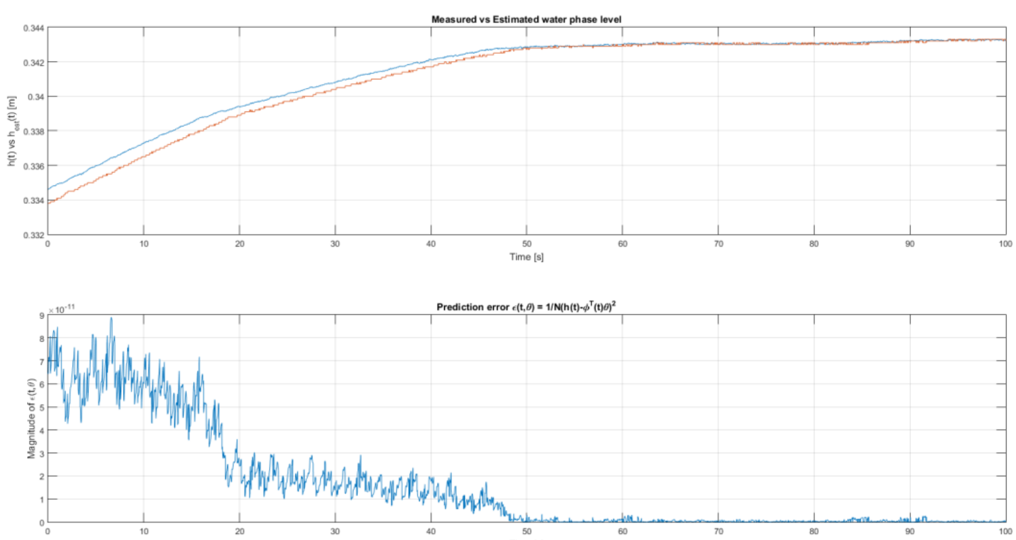

Fig. 2.2.4.2.2.Window two Measured vs Estimated water phase level

The data in Fig. 2.2.4.2.2 is again following the measured water phase level with permissible error. Due to the linear characteristics of the second window of data, the prediction error converges to zero faster in comparison with the prediction error for the first window, resulting in even better fit of the predicted water phase level.

2.2.4.2.1 Summary

Several main conclusions regarding the analytical solution of the defined least square problem are obtained during the implementation phase. First of all the two parameters associated with the two considered windows of data are promising. The magnitude of the prediction error for both widows is “small” and converges to zero after given period indicating that the predicted water phase level is close to the measured water phase level.

The analytical approach for estimating values of the unknown parameters θ is a straight forward solution given the fact that the required set of data used in the calculations is known. However, with relevantly big data set the computation load become heavier. The observed time required to obtain water phase level prediction for one window of data is approximately three and a half hours. Considering the time limits and the computational power required only two out of the four data windows are used to obtain parameter estimation. Furthermore, using the considered data set, an inverse of the required matrix used to obtain estimates for the considered parameters was challenging to obtain. A psudoinvers is considered for the numerical computations instead.

Finally yet importantly, the two obtained water phase level predictions associated with the estimation of the given unknown parameters are proving that the considered linear least square method is working for small parts of the data. However, the associated parameters are minimizing the prediction error for each window of data, but prediction of the water phase level in the full span of the considered experiment is not obtained. Conclusion that a recursive least square method should be implemented, in order to minimize the computational load and obtain prediction of the water phase level over the full data set of “Experiment Two”, is reached.

2.2.4.3 Recursive least square Solution

Considering that, the analytical solution for estimation of the unknown parameters is computational heavy, due to the reason that invers of matrix with dimensions 50000x50000 is required to obtain prediction of the water phase level recorded during “Experiment Two”, a recursive least square (RLS) estimation procedure is applied. Moreover, an efficiency matrix invers algorithm [5] is considered, in order to lower the computational power demands further by avoiding the otherwise necessary matrix inversion at each step of the estimation procedure. Introducing relationship (3.2),

$$P(t) = [\varphi^T(t)\varphi(t)]^{-1} \tag{3.2}$$

and making use of the matrix inversion lemma along with a recursive approach for obtaining the unknown parameters is calculated based on (3.3).

$$\hat{\theta}(t) = \hat{\theta}(t-1) + L(t)\big[h(t) - \varphi^T(t)\hat{\theta}(t-1)\big] \tag{3.3.a}$$

$$L(t) = \frac{P(t-1)\varphi(t)}{\lambda(t) + \varphi^T(t)P(t-1)\varphi(t)} \tag{3.3.b}$$

$$P(t) = \frac{1}{\lambda(t)}\left[P(t-1) - \frac{P(t-1)\varphi(t)\varphi^T(t)P(t-1)}{\lambda(t) + \varphi^T(t)P(t-1)\varphi(t)}\right] \tag{3.3.c}$$

)

Equation (3.3) is defining a RLS algorithm used to estimate the unknown parameters associated with each input of the system. Every new value to be estimated is obtained in terms of the previous estimated value and the prediction error scaled by the *L(t)* term representing the relative information value in the latest available moment. Following the rule of thumb, the forgetfulness factor is set to value of 0.98 The following results are obtained after the combination of all estimated unknown parameters.

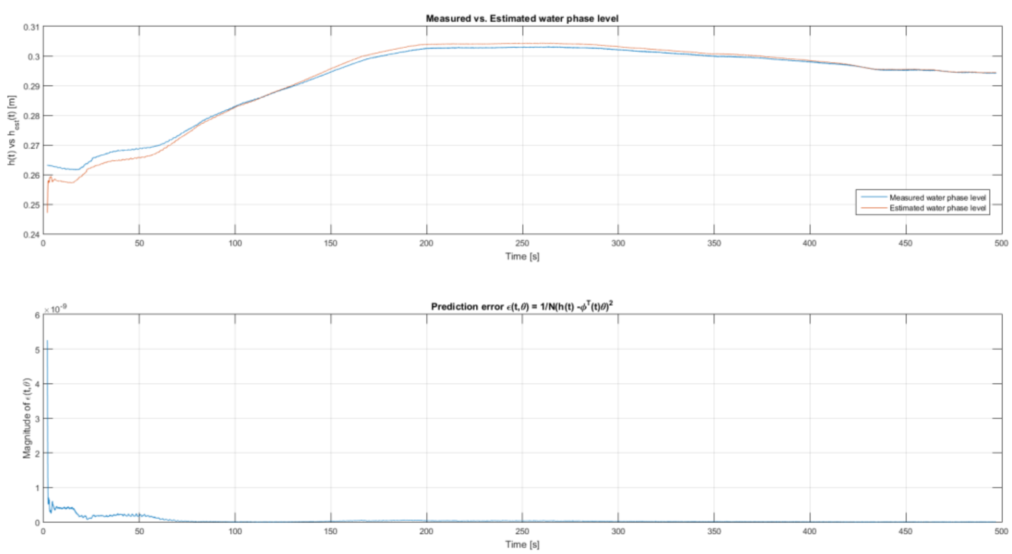

Fig.2.2.3.4.1. Measured vs Estimated water phase level using RLS

The predicted water phase level is fitted into the measured water phase successfully. The highest prediction error is observed in the beginning of the simulation, due to the zero initialization of the RLS algorithm. As proceeding further with the estimation procedure, the prediction error is rapidly converging trough zero, providing enough evidence to consider the obtained model as accurate mathematical representation of the considered water phase level.

2.2.4.3.1 Summary

Recursive implementation of the least square solution has many advantages. First, finite dimensional vector is used for the numeric calculations involved in the parameter estimation procedure, resulting in significant reduction in the required computational power.

Second, by applying an efficiency matrix invers algorithm, heavy operations involving the inversion of a matrix are not required anymore, minimizing the computational load further.

Third, the required time for computing results of the estimated values for the unknown parameters is significantly reduced allowing much more freedom in the simulation process.

Finally, by using a RLS algorithm both off-line and on-line parameter estimation can be performed, providing the opportunity to obtain estimated values for the unknown parameters from both already obtained data set, or calculating the desired values in real time.

2.3 Conclusions over system identification procedure

Interesting observations and practical knowledge is obtained during the implementation of the system identification loop defined in “Chapter II Section 2”. Executing each step sequentially provides straight forward direction to obtain model representing the water phase level dynamics.

By investing time into the derivation of a first principle model, clear definition of all inputs and outputs influencing the water phase level is obtained, providing prior knowledge for the system. This information is then used as starting point for the required experiments design.

Five experiments considering different operating conditions are designed and executed sequentially over time. Each experiment is defined by the average values recorded during ten sequentially executed trials of the considered experiment. Two out of the five experiments are selected for this study.

The goal pursued with the first experiment is to obtain transient response of all considered variables of interest using simple step excitation for all inputs, providing clear view of internal relationships and time constants associated with each variable of interest. Finally, the evaluated results from the first experiment are used as starting point for the designed of the next experiment in line.

The second experiment is orientated entirely to illustrate the dynamics of the water phase level under slug inlet flow conditions. The experiment provides enough informative data for an estimation procedure. However, the design of the second experiment is considering only the lower band of flows allowed to enter the system, implying that some dynamics of the system are not entirely captured. Future work is required in order to obtain a maximum informative data set.

In general the experiments design is one of the most complex and time consuming part of the system identification procedure. Well thought experiments considering all factors influencing the water phase level is difficult task to carry. Over the experimental phase deeper knowledge of the considered process and lab setup is obtained, also providing an informative set of data used to estimate a model describing the water phase level of a tree phase gravity separator system.

After obtaining the required data set an ARX model structure is selected to describe the water phase level. The model is linear combination of the defined inputs, leading to conclusion that the estimation of the unknown parameters associated with each input can be carried separately by splitting the considered model into four parts each illustrating the relationship between one input and the water phase level. Furthermore, a least square criterion of fit is chosen to minimize the prediction error between the measured and simulated water phase level. Two solutions providing estimate of the unknown parameters associated with the selected model are considered.

An analytical least square solution is applied first, leading to the following conclusions. A derivation of the parameter estimator is straight forward procedure, however an inverse of the constructed matrix was hard to obtain, implying that the obtained matrix is badly scaled. The pseudoinverse of the considered matrix is used to proceed with the estimation procedure. Furthermore, by applying the analytical least square solution the computational load demands are increased significantly, resulting in incapability to obtain simulation over the full time range of the experiment. Instead shorter periods of time are used to estimate parameters for portion of the measured water phase level, concluding that the analytical least square solution is capable of estimating the considered unknown parameters.

A recursive least square solution is applied next. It is observed that the computational demand is significantly lowered. Furthermore, by applying an inverse efficiency matrix algorithm, the inversion of the obtained matrix at each iteration step is no longer required, improving even further the efficiency of the RLS. In trade off the implementation of such algorithm is complex and time consuming. Different considerations must be taken into account to obtain estimates of the unknown parameters.

The two used least square solutions have different tradeoffs and limitations. The analytical solution is based only on already predefined data forming an offline parameter estimation procedure, in comparison with the recursive implementation which can be used in an online manner, estimating the unknown parameters in real time. From computational point of view the RLS is better performing, but more complex to implement in comparison with the analytical solution.

The final step considered is the comparison between the simulated and measured water phase level. Based on the obtained simulation results it is proved that the recursive least square parameter estimation is successful. Model regarding the water phase level is obtained, with relatively small prediction error in agreement with the project specifications.

2.4. Open loop system

After obtaining values representing the unknown parameters and a model is chosen from the defined model set four transfer functions representing the relationship between each considered input and the water phase level are obtained as follow.

$$H_1(q,\theta_b) = \frac{B(q)}{A(q)} \tag{3.4.a}$$

$$H_2(q,\theta_c) = \frac{C(q)}{A(q)} \tag{3.4.b}$$

$$H_3(q,\theta_d) = \frac{D(q)}{A(q)} \tag{3.4.c}$$

$$H_4(q,\theta_k) = \frac{K(q)}{A(q)} \tag{3.4.d}$$

Each transfer function is defined by two polynomials, where the unknown parameters are used as numerator and denominator coefficients. The following block diagram is illustrating the open loop system as follow.

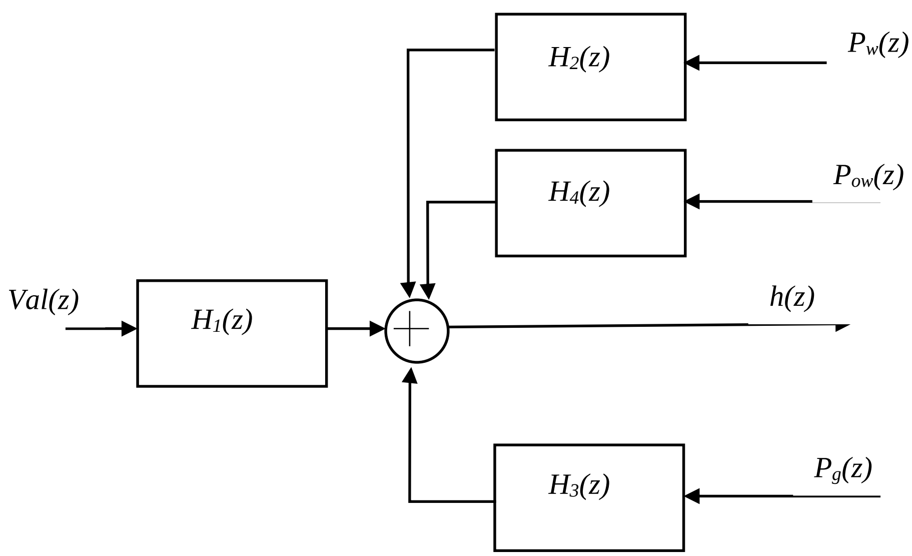

Fig.2.4.1 Block diagram open loop system

Each transfer function is of first order. The transfer function with suffix 1 is representing relationship between the water phase level and the control valve, providing manipulated input to control the water phase level. The following three transfer functions are associated with the relationship between each measured disturbance and the water phase level. Considering that, the defined in (3.4) transfer functions are expressed as functions of the estimated parameters and the backwards shift operator, discreet form for all transfer functions and signals is chosen to evaluate the open loop system. Furthermore, all defined measurable disturbances are defined through individual transfer function, providing additive relationship between to describe the open loop system.. It is observed that all transfer functions are stable with poles located inside the unit circle, with consideration that the value of all poles are close to one ,leading to conclusion that the open loop system is stable but close to marginal stability . The simulated water phase level is compared against the measured in the following graph

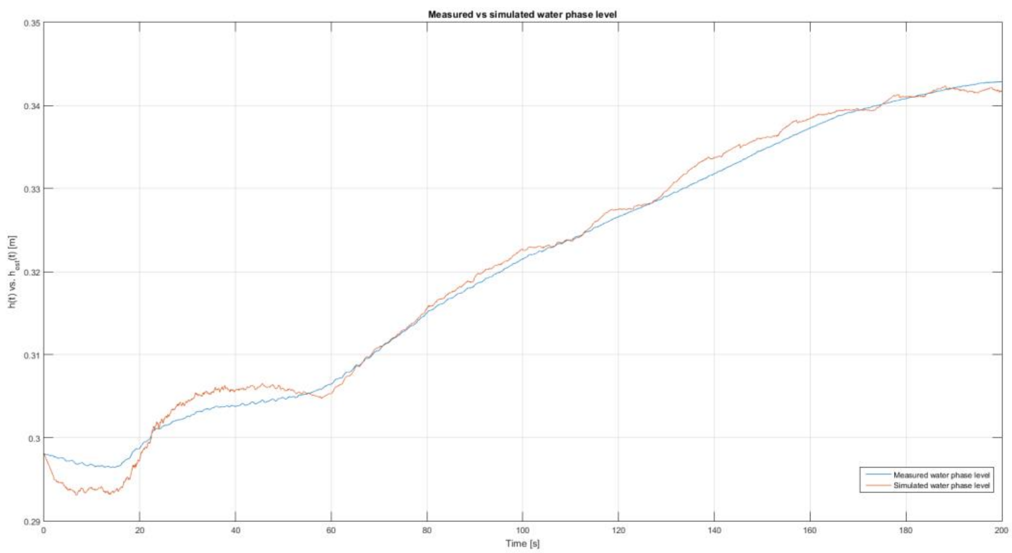

Fig.2.4.2 Measured vs. Simulated water phase level

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Several important observations are obtained from Fig.2.5.2. First the simulated water phase level is tending to follow the measured water phase level with permissible error, however this is valid only over the time period between zero and two hundred seconds. After the two hundred seconds marker oscillations are starting to occur in the simulated water phase level, resulting in significant difference between the measured and simulated water phase level.

Possible reason for the strange behavior of the open loop system might be caused by the measurement disturbances going along with each considered signal. The parameter estimation is performed under noise free environment, resulting in idealized model, which is considered to be one reason for the observed unwanted oscillations, leading to relatively big difference between the measured and simulated system output after two hundred seconds within simulation time. Furthermore, considering that linear models are defined for small deviations from given operating point, second possibility for the obtained error in the end of the simulation is that the system is going further from the default operating point as the simulation time grows.

Considering the open loop system response and the limited portion of the simulation where measured and simulated water phase level are overlapping, a decision is made to proceed with the evaluation of a closed loop system by applying a PI control structure to the considered model.

2.5 Closed loop system

Proceeding further a block diagram of the closed loop system, including a PI controller is presented in the following diagram.

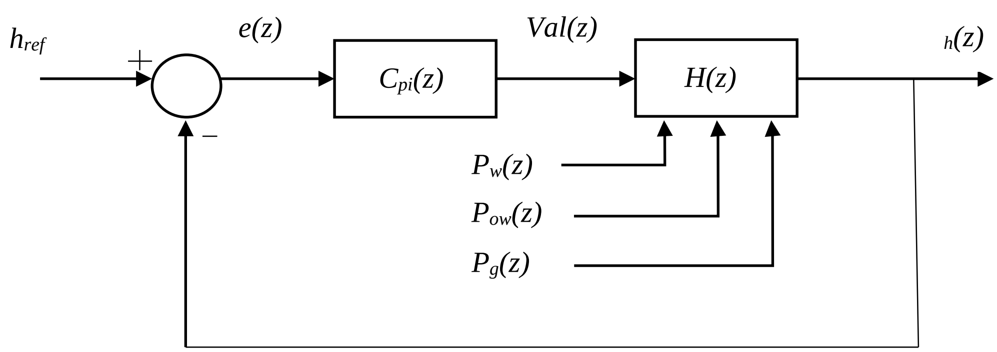

Fig.2.5.1. Closed loop system

The system model H is closed in a feedback control loop, where all measurable disturbances are introduced in a feed forward manner and control over the manipulated input is applied, The error signal (3.5) inputted to the considered PI controller is defined as the difference between reference water phase level and measured process output.

$$e(z) = h_{ref} - h(z) \tag{3.5}$$

Proceeding further a discreet PI control structure of the following form is used to correct the defined in (3.5) error signal.

$$C_{pi}(z) = P(1 + IT_s \frac{1}{z-1}) \tag{3.5}$$

The proportional and integral gain are obtained using the ”PID tool” software provided from Matlab. Finally, the corrected signal is inputted to the water phase outlet flow valve, providing control over the water phase level.

Two PI control structures are considered. First, a controller which responds slow to change in the set point is applied to the closed loop system. Second, a significantly fast response controller is introduced to the system. Comparison between the two controllers is illustrated below.

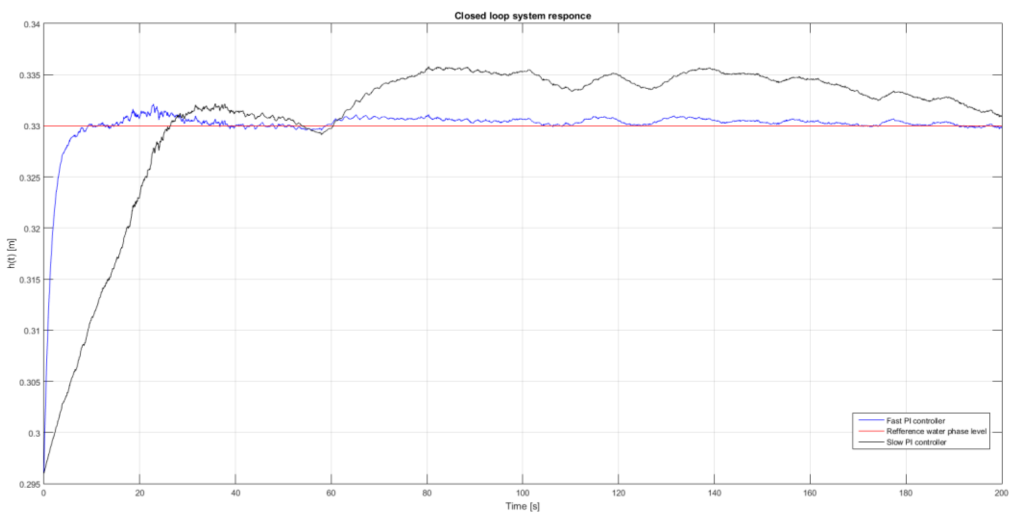

Fig.2.6.1 Closed loop system response

Based on the simulation results several important conclusions are obtained regarding the application of a PI controller considering the selected model. The fast controller which has properties of tree seconds rise time, five seconds settling time, small proportional gain and integral gain of two hundred, is capable of bringing the system to steady state and following the reference set point t almost without any deviations. However, a more reasonable controller which considers rise time of one minute, settling time of one minute and a half and slightly higher proportional and integral gains is tracking the reference point with bigger offset error. Furthermore, it is observed that oscillations are occurring in both close loop system responses. When more aggressive controller is applied the oscillations are dampened and better reference tracking is achieved, when a “relaxed “controller is applied bigger oscillations in the water level are occurring. Finally based on both simulation results, it is concluded that tradeoff between the two PI controllers is required in order to obtain band controller capable of maintaining stable operating conditions while the water level is deviating in permissible range.

Project Conclusions

The project requirements are reached. Utilizing the set of defined specifications a mathematical model representing the water phase level is obtained. By following a system identification proceeded in combination with first principle model, an ARX model structure is defined.

Proceeding, further values for the unknown parameters associated with the defined model are estimated based on linear regression predictor. Given the through experiment, obtained data a prediction of the water phase level is obtained, such that the estimated parameters are minimizing a least square criterion function associated with the prediction error of the considered model.

Two methods for obtaining the parameter estimates are used. Analytical least square solution is obtained. It is concluded that such approach is simpler to implement given that the obtained data is informative enough and invers of the data coronation matrix exist. Associate tradeoffs with such approach are the computational load required, the execution time and limitation of parameter estimation in offline manner. The second approached used is a recursive least square solution concluded to be more time consuming and complex in implementation, but provides significant reduction in computational load, execution time and provides options for online parameter estimation.

Based on the obtained results from both least square solutions is concluded that both analytical and recursive least square solution are capable of predicting the water phase level inside a three phase gravity separator with similar prediction error. However due to the computational demands and the size of the considered data set, only portions of the data are used to obtain prediction of the water phase level, resulting in uncertainties that an estimation over the whole range of the data will be as accurate as estimation for small part of the data. From which follows that the recursive least square solution, which is capable of providing prediction over the full data set, must be considered for the parameter estimation procedures.

Based on the obtained values for the unknown parameters an open loop system model describing the water phase level is constructed. By defining the obtained parameters as coefficients of transfer functions representing the relationship between given input to the system and the water phase level a Simulink block diagram is obtained, providing open loop system response.

Comparing the open loop system response with the measured water phase level is observed that the simulated response is capable of tracking the measured values up to two hundred seconds simulation time. After that limit, the simulation starts to differ significantly from the measured water phase level, indicating that using an idealized model without noise considerations might cause the open loop system response to behave strange considering simulation using the actual measurements obtained from the lab setup.

With considerations regarding the open loop system response and using the portion of the data where open loop system response tends to be close to the measured water phase level a closed loop system is obtained. Two different PI controllers with different characteristics are applied to the system.

The first controller is defined to be "aggressive" and react fast in order to track a reference point. The second controller used is a "relaxed" PI controller reacting slower to a change in the set point. The obtained results are evaluated and compared. It is concluded that the aggressive controller is compensating for the process disturbances and is capable of tracking a reference point with almost negligible offset; however, oscillations in the water phase level are still visible. The “relaxed” PI controller have slower response time allowing bigger offset accumulation in the closed loop system, also greater oscillations of the controlled water phase level is observed.

From the obtained results regarding the closed loop system is concluded that a band controller, containing combination of both evaluated PI structures, can be used to achieve deviations of the water phase level in predefined range.

3.1 Future work

Considering the obtained knowledge and observations through the project several interesting and important points are considered for future work related to this project.

First, an addition of measurement noise model to the derived model will be considered, in order to obtain more accurate description of the considered system. Furthermore, efforts will be put in investigating the reason behind the strange behavior of the open loop transfer function model implementation.

Further evaluation of PI controllers applied to the closed loop system must be considered. A band controller implementation will be evaluated as combination of the defined controllers. Moreover, at this point only theoretical simulations of the closed loop system are considered. Practical implementation along with the derived recursive algorithm will be applied in real time in order to apply control over the water phase level and obtain measurements regarding the closed loop system.

Finally, following the same manner model representing the gas and oil phase will be derived in the same manners as the produced water phase level model in order to obtain fully description of a three phase gravity separator system.

List of Figures

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