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# Plant-wide Control for Better De-oiling of Produced Water in Offshore Oil & Gas Production ⋆

**Zenyu Yang** * **Jens Peter Stigkær** ** **Bo Løhndorf** ***

* *Department of Energy Technology, Aalborg University, Esbjerg Campus, Niels Bohrs Vej 8, 6700 Esbjerg, Denmark (e-mail: yang@et.aau.dk).*
** *Maersk Oil A/S, Kanalen 1, 6700 Esbjerg, Denmark (e-mail: Jens.Peter.Stigkaer@maerskoil.com)*
*** *Ramboll Oil & Gas A/S, Willemoesgade 2, 6700 Esbjerg, Denmark (e-mail: BOL@ramboll.com)*

**Abstract:** This paper discusses the application of plant-wide control philosophy to enhance the performance and capacity of the Produced Water Treatment (PWT) in offshore oil & gas production processes. Different from most existing facility- or material-based PWT innovation methods, the objective of this work is to propose a software-based breakthrough PWT innovation solution. This is achieved through integration of an intelligent anti-slug control with a coordinated separator and hydrocyclone control. Some undergoing work and results are also introduced. The proposed solution will promote a completely new generation of PWT system in terms of better environmental protection, along with significantly improved production and reduced cost-vs-production ratio.

*Keywords:* Large-scale complex systems, plant-wide control, bifurcation, Oil & gas production

## 1. INTRODUCTION

To meet the increasing energy demand, oil & gas will continue to be world's major energy source in the 21st century. Furthermore, approximately 30% of the current global oil & gas production is from offshore and the oil industry expects this share to grow continuously in the future. In last decade, oil companies produced an average of three barrels of water for each barrel of oil (Bailey *et al* (2000)). The mature oil fields produce an increasing amount of water. It is not a rare case that well streams from old fields contain 90% water or even more, that is mainly due to the increased amount of injected water into the reservoirs so as to maintain the reservoir pressure (Robinson (2007)). After separation, de-oiling and degassing procedures, a portion of produced water is re-injected into the fields, and the rest is discharged directly to the sea (Ray and Engelhardt (1992)).

The produced water in the offshore oil & gas production is a mixture of organic and inorganic compounds. It is firmly prohibited to be discharged into environment directly. In recent decade, the international regulations for disposal of hydrocarbons to sea are also becoming more and more strict, especially after the Gulf Oil Spill accident (Ahmadun *et al* (2009)). For instance, the EU Water Framework Directive launched in 2000 is aimed to zero discharge of pollutants. Norwegian oil operators have started to implement zero environmental harmful discharge since 2005. The OSPAR commission has agreed on zero discharge of pollutants into the sea since 2008. Under this circumstance, most oil & gas companies around the world are pursuing the implementation of "zero-discharge" capability (Ahmadun *et al* (2009); Robinson (2007)).

The Produced Water Treatment (PWT) can be categorized as stand-alone or combined physical, biological and chemical treatment processes etc (Ray and Engelhardt (1992); Sinker (2007)). Due to the large volume being produced, every year more than 40 billion USD is used to deal with the produced water within the oil & gas production industry (Bailey *et al* (2000)). For example, the cost for handling water can be as high as 4 USD per barrel of oil produced from a well which production has 80% water cut (Bailey *et al* (2000)). There is no doubt that any innovative PWT control technology can benefit the global oil & gas business from the perspectives of significant cost reduction and improved oil & gas production, as well as protection of the environment (Bailey *et al* (2000); Husveg *te al* (2007); Ray and Engelhardt (1992)).

By the end of 2012, the Danish National Advanced Technology Foundation decided to support a three-year research project, named *Plant-wide De-oiling of Produced Water using Advanced Control (PDPWAC)* with a total budget of 10 mill DKK. The project is cooperated between Aalborg University and two Danish oil & gas companies - Maersk Oil A/s and Ramboll Oil & Gas A/s. Different from these new facility- or material-based PWT methods, the PDPWAC aims to propose a software-based breakthrough PWT solution. Through cooperatively synthesizing and integrating an advanced PDR control,

⋆ Supported by the Danish National Advanced Technology Foundation through PDPWAC Project (J.nr. 95-2012-3).

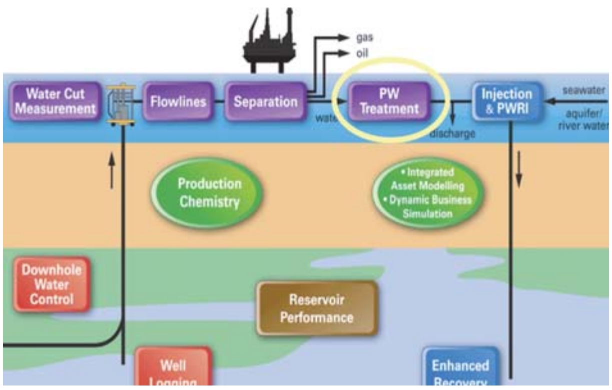



Fig. 1. Overview of water circulation in offshore oil & gas production (Robinson (2007))

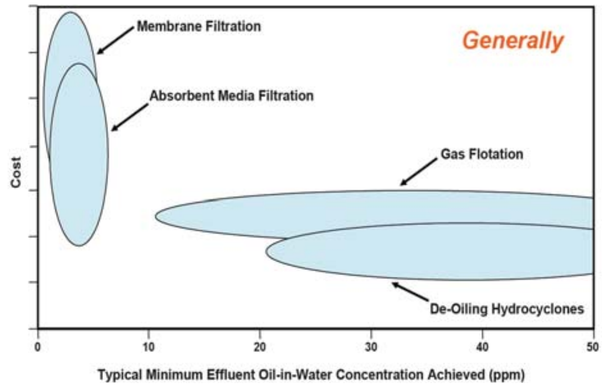



Fig. 2. Classification of typical PWT techniques in terms of performance vs cost (Sinker (2007))

averaging separator water level control and well-pipeline-riser anti-slug control together based on the plant-wide control principle, the de-oiling of the produced water can be significantly improved with higher hydrocyclone efficiency, along with improved oil & gas production rates and reduced cost-vs-production ratio. This paper gives a brief introduction of this project and some undergoing topics and obtained results.

The rest of the paper is organized in the following: Section 2 introduces the plant-wide scope of the considered relevant systems; Section 3 presents the plant-wide control principle, and accordingly the problems needed to be handled under this framework; Section 4 discusses some of undergoing work and results; finally we conclude the paper in Section 5.

## 2. OFFSHORE PWT RELEVANT SYSTEM AND PROBLEM

Instead of just focusing on the PWT facility in the production platform, we take a overall look of the entire production process. The circulation of the produced water in offshore oil & gas production can be sketched as shown in Figure 1. Firstly the water in the reservoir is pushed by the reservoir pressure into the production wells along with the oil and gas fluids. Then, the well fluids including the water are transported from the satellite platform to the production platform through a pipeline lying on the seabed. On the production platform, one or a set of three-phase separators are employed to primarily separate the water, oil and gas (Yang *et al* (2010)). Afterwards, the separated water is further fed into the PWT facility for de-oiling purpose. A portion of the treated water is discharged to the sea, while the other portion of the treated water is re-injected into the reservoir through the rejection wells.

Right now, the most popularly used device for de-oiling of produced water in oil & gas industries is some hydrocyclone-type of facility (Eren *et al* (1997); Husveg *te al* (2007); Ray and Engelhardt (1992)). Because of no requirement of use of chemicals or driving energy, the hydrocyclones provide a cheapest solution with a reasonable separation capability (20 ppm) as shown in Figure 2. In practice, however, the operational efficiency of hydrocyclone is very sensitive to fluctuations in the inflow rate (Eren *et al* (1997)). Even though it has been noticed that a control of the Pressure Drop Ratio (PDR) of hydrocyclones is very critical (Ray and Engelhardt (1992)), as we discovered, most of existing commercial PDR controls are still some types of PID-controller based trial and error solutions. This situation makes it very hard or even impossible to optimize these types of solutions (Husveg *te al* (2007); Sinker (2007)).

Alternatively, some other new techniques, such as the membrane filtration technique, could be used in the PWT for offshore production. However, the adaption of this new technique needs to completely change the current PWT facilities. Similar issue is observed for almost all of the available new commercial PWT solutions, i.e., more or less some extra facilities or extensive chemical materials are needed to be installed or added together with the existing PWT systems. Besides that, whether these new facilities or techniques are able to stand with the diverse and harsh offshore operational condition and satisfy the required large treatment capacity, as well as the limitations of weight and occupied space etc, are not clear at this moment. Different from these new facility- or material-based PWT methods, some cost-effective PWT solution to improve the water treatment quality and efficiency of the existing facilities and systems is more promising and urgent from the practical and industrial operational point of view (Havre and Stray (2000); Sinker (2007)).

Like most of chemical/petroleum process systems, the offshore oil & gas processing system is very large-scaled and complicated, but allocating in a quite limited spatial space (production platform) with strictly limited weights plus extremely high safety requirements. Thereby, most of offshore processing systems are usually heavily coupled and interacted with each other at a very high autonomous level. To develop or even just improve these sophisticated safety-critical systems is challenging and far from trivial. This PDPWAC project aims to employ the intelligent plant-wide control methodology to propose a software-based breakthrough PWT innovation solution.

## 3. INTELLIGENT PLANT-WIDE CONTROL

By combining some intelligent modeling and control techniques with the plant-wide control philosophy, the *intelligent plant-wide control* concept will be adopted to develop our new cost-effective PWT solution.

### 3.1 Plant-wide Control Philosophy

The plant-wide control principle has been extensively used in process control society, even though it has not yet been receiving enough emphasis in control society (Larsson and Skogestad (2000)). The reasons for adopting this philosophy here lie in the following aspects:

- The plant-wide control not only takes care of the control type design and control parameter selections, but also provides an opportunity to systematically handle control structure design and analysis, which is often an unavoidable headache for any process control development in practice;
- The control structure design provide the extraordinary opportunity to maximally utilize the degrees of freedom hidden among interactive subsystems, mitigate the potential conflictions between subsystems, and balance the resource distribution among subsystems, so as to possibly achieve "all-win" solution(s);
- Evidences we observed from a number of industrial partner owned platforms indicate that most current PWT control solutions seem not to be developed in a plant-wide sense at all (Yang *et al* (2010, 2012)). In most situations, the overall system was assembled by different subsystems which were developed and produced from different vendors, and many subsystems were even developed and installed at different time periods.

Thereby, there is a huge opportunity to optimize the operation of these already-assembled large process systems by using the plant-wide control concept in an all-win manner.

### 3.2 Intelligent Modeling and Control

Using the Artificial Intelligence (AI) techniques for system modeling and control development has attracted more and more attentions in control society, especially, concerning to large scale complex systems. We have experienced a lot of good observations by using the Genetic Algorithms (GA) for simple process model approximation (Yang Seested (2013)), modeling the features of variable speed pumps (Pedersen and Yang (2008)), Estimation of hydrocyclone performance index using Neural Network (Eren *et al* (1997)) and optimization of multiple pump scheduling (Pedersen and Yang (2008)). We believe that the AI techniques will benefits our project in terms of cost-effective model identification, constraint non-convex optimization, supervisory and coordination control etc.

### 3.3 Focused Problems

As shown in Figure 3, the following three topics are focused in the project:

- A innovative plant-wide separator level and hydrocyclone control;
- A plant-wide Multi-Input-Multi-Output anti-slug control; and
- Integration of separator, hydrocyclone and slug flow controls.

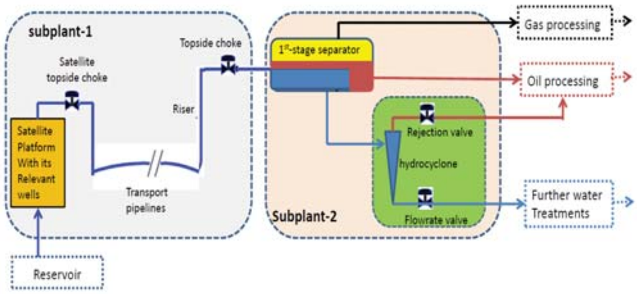



Fig. 3. Sketched diagram of different focused sub-plants according to a typical oil & gas production process

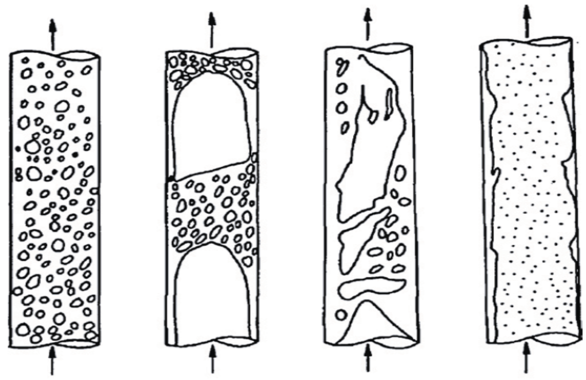


Fig. 4. Different flow patterns. From left to right: Bubble flow, slug flow, churn flow, annual flow and wispy annular flow (Taitel *et al* (1980))

## 4. SOME UNDERGOING WORK AND RESULTS

### 4.1 Slugging Flow Phenomena

In a typical oil & gas production process, the gas and liquid may not be evenly distributed throughout the pipeline under some operating condition, so that sometimes the liquid and gas travel as large plugs with mostly liquids or mostly gases through the pipeline. These large plugs are referred to as slugs (Godhavn *et al* (2005); Meglio *et al* (2010)). This irregular slugging flow can result in very poor oil and water separation, limits the production capability and even causes flaring (Havre and Stray (2000)).

The slugging phenomena can happen in many different locations in the production process as shown in Figure 1, such as, the slugging flow from the gas-lifted production well due to the casing-heading mechanism (Eikrem (2006)); Terrain slugging which is caused by the elevations in the pipeline by following the ground elevation or the sea bed (Havre and Stray (2000)), and the most popular riser slugging phenomenon (Jahanshahi *te al* (2012); Ogazi *et al* (2010); Storkaas and Skogestad (2007)). Different located slugs subject to different mechanisms need to be carefully understood and handled.

### 4.2 Emulation of Slugging Flow in a Lab-scaled Facility

An economic lab facility for emulating a slugging flow phenomenon in the offshore oil & gas production is constructed in our laboratory (Hansen *et al* (2013)). A photo of the most part of the setup is illustrated in Figure

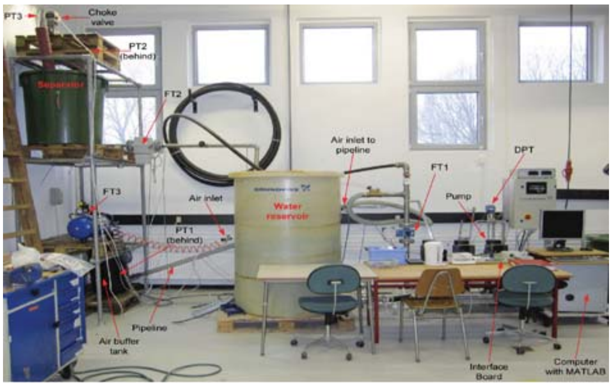


Fig. 5. Photo of AAU's slugging flow lab facility

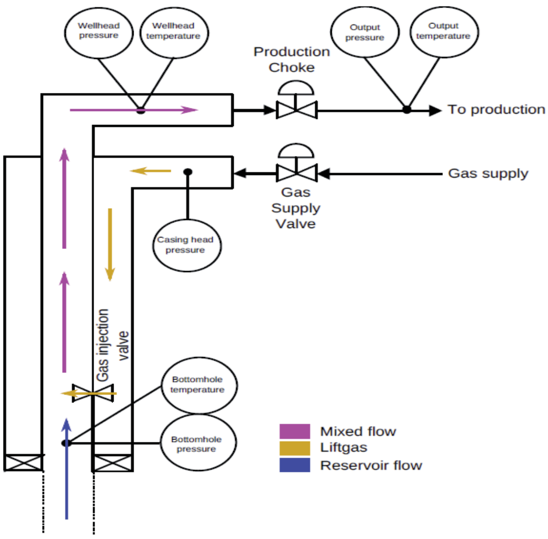



Fig. 6. Schematic diagram of a gas-lifted production well

5. This facility is so flexible that it can be adapted to emulate either the riser slugging phenomenon (Hansen *et al* (2013)) or the gas-lifted casing-heading slug problem (Jepsen *te al* (2013)). We refer to Hansen *et al* (2013); Jepsen *te al* (2013) for more details.

### *4.3 Modeling and Control of Slugging Flow in a Gas-lifted Production Well*

In the oil & gas production, an approach known as gas-lift production well is often employed in order to cope with a low reservoir pressure. An controlled amount of gas is continuously injected into the reservoir or well to increase the reservoir pressure or lower the density of fluid inside the well, so as to keep a productive flow rate through the production system (Eikrem (2006)). A sketched diagram of a gas-lifted production well is shown in Figure 6.

The gas-lift approaches can maintain a reasonable production rate, however, some instability can be also easily caused, which is reflected by largely and regularly oscillated pressure and flow measurements under static operating conditions. This is also known as casing-heading instability problem in the oil & gas production processes.

A simple mathematical model of the flow dynamic in the production well is investigated and tested in the lab facility by Jepsen *te al* (2013). The casing-heading induced

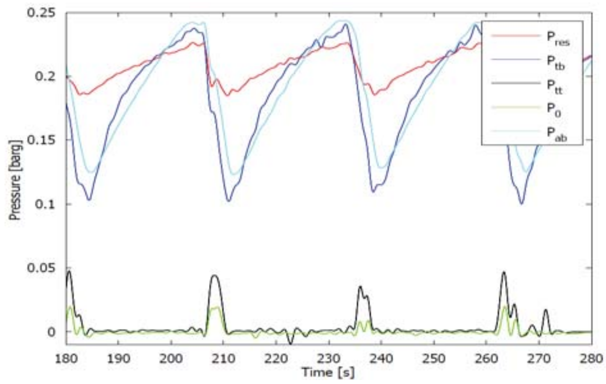



Fig. 7. Measurement data from lab-setup under slugging flow, where $P_{res}$ is the reservoir pressure; $p_{tb}$ is the tube down-hole pressure; $P_{tt}$ is the tube top-side pressure; $P_0$ is the choke valve's downstream pressure; $P_{ab}$ is the annulus pressure

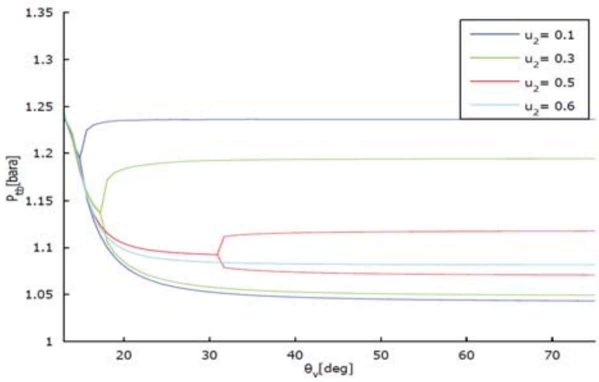


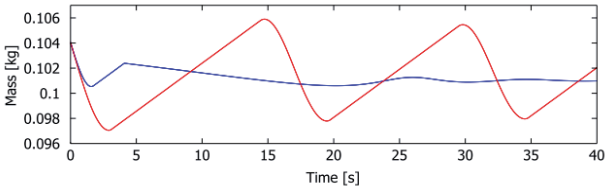

Fig. 8. $P_{tb}$ pressure bifurcation maps generated w.r.t. different topside choke-valve position ($\theta_v$ : %) and gas feeding rates $u_2$

slugs can be easily observed as shown in Figure 7. The bifurcation problem w.r.t. the topside choke valve position is illustrated in Figure 8.

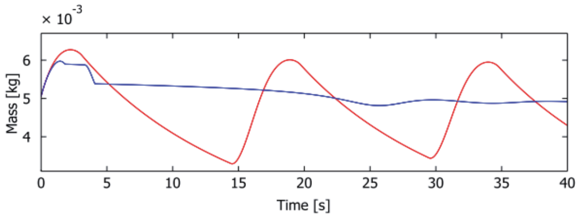
An estimator-based full-state feedback controller is developed based on linearizing the obtained nonlinear model. The pole placement method is used to derive the control parameters as well as the estimator parameters. A simulation result of the controlled system based on the nonlinear model is shown in Figure 9. It can be clearly observed that the original system (without control) is unstable while the controlled system turns to be stabilized using the designed controller. Furthermore, the production rate under the stabilized system is larger than any production rate subject to open-loop stability (Jepsen *te al* (2013)).

### *4.4 Modeling and Control of Riser Slugging Flow*

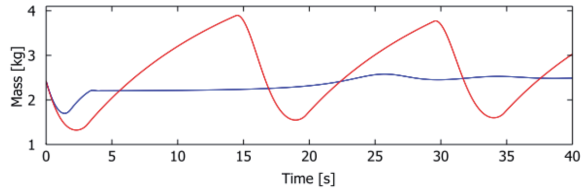
The constructed lab facility can be adapted to emulate the riser slugging problem, as shown in Figure 10. Figure 11 illustrates the cyclic (slugging) behavior of a vertical riser pipeline: Phase-(1) Liquid accumulates at the bottom of the riser; phase-(2) When more gas and liquid enters the system, the pressure will increase and the bottom of the riser will be filled with liquid; Phase-(3) After the blocked gas has built up, the pressure will be large enough to blow the liquid out of the riser; Phase-(4) After the



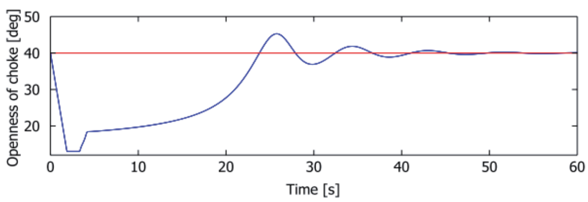
(a) Mass of gas in the annulus, $x_1$



(b) Mass of gas in the tubing, $x_2$



(c) Mass of liquid in the tubing, $x_3$



(d) position of the choke valve, $\theta_v$

Fig. 9. Simulated stabilization of unstable operating point: red without controller and Blue is with the designed controller

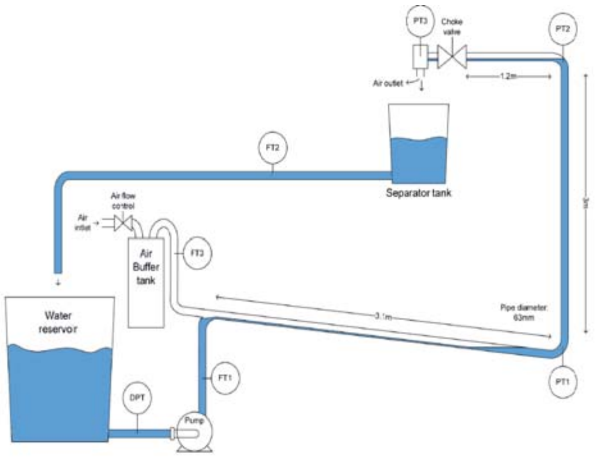



Fig. 10. Sketched diagram of the adapted lab setup for riser slugging study

blow-out, the liquid will start to build up in the bottom of the riser and the cycle repeats (Jahanshahi *te al* (2012); Storkaas and Skogestad (2007)).

A nonlinear model for the riser flow dynamic is developed in Hansen *et al* (2013). A validation of the developed model is illustrated in Figure 12, where it can be observed that the model has quite reasonable precision in reflecting the slug phenomenon. However, the slug control of this

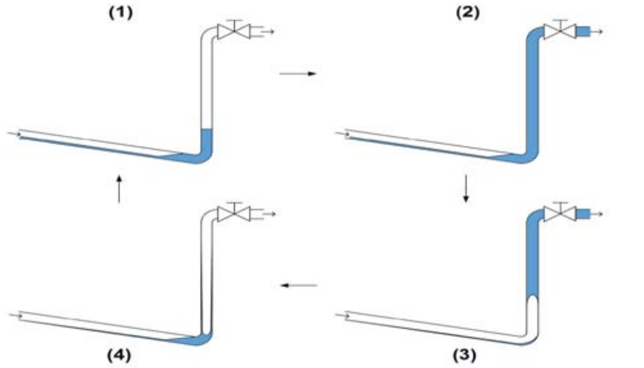



Fig. 11. Illustration of the cyclic behavior in a riser pipeline when slug occurs. A controllable choke valve is placed at the top of the riser.

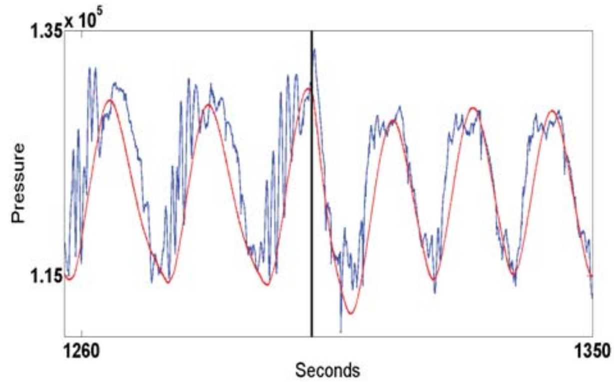



Fig. 12. Simulated riser bottom pressure(red) compared to measured pressure(blue). The vertical line indicates a step from 50% to 95% choke valve opening reference

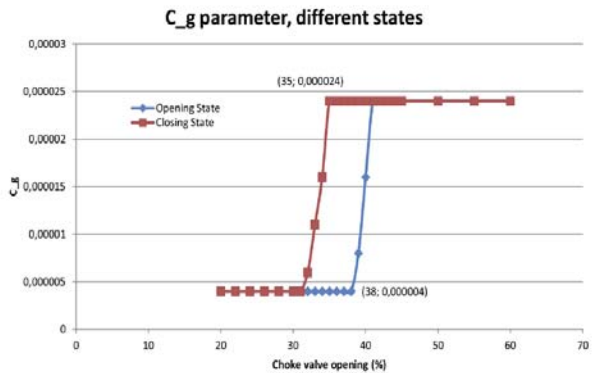



Fig. 13. Identified hysteresis phenomenon of the choke-valve's orifice coefficient

riser slugging problem is far beyond any standard control strategy (Godhavn *et al* (2005)), especially for our setup, where a hysteresis phenomenon of the operation of the riser topside choke-valve can be clearly observed. This valve's orifice coefficient identified through experiment is shown in Figure 13. Some adaptive/switching nonlinear model predictive controller is under investigation right now. We expect that we can report the latest results at the conference.

### *4.5 Other investigations*

In order to balance the level set-point control and the smoothness of the water outflow rate, one of our previous work Yang *et al* (2010) has proposed a novel averaging separator water level control method. Yang *et al* (2012) studied the optimal control and scheduling of boosting pumps. To extend these results into our project is one of current focus as well. Meanwhile, to adopt and extend our latest GA identification results (Yang Seested (2013)) for on-line estimation purpose is also under going. We expect to report more results in the near future.

## 5. CONCLUSION

This paper introduces an undergoing project which aims for promoting the de-oiling capacity and quality of produced water in the offshore oil & gas production, with improved production rates, reduced environmental footprint, and meanwhile decreased cost-vs-production ratio, by employing an intelligent plant-wide control methodology. Some of undergoing work and results have shown the promising feasibility to achieve this goal.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