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Fast Model Based Approximation of the Closed-loop Performance Limits of Gas/Liquid Inline Separators for Accelerated Design

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Abstract: A current trend in the oil and gas industry is to use compact so called inline separators (ILS). Unlike their large conventional counterparts, the operation of these separators is very sensitive towards variations in the multiphase flow to be separated. This sensitivity easily results in operational problems and economic loss and may prohibit the application of ILS, in particular as many current production operations are facing large slug flow type of variations. One way to reduce the ILS sensitivity towards flow variations is via improved control. Here, motivated by the industrial need for cost-effective compact separators with sufficient flow variation handling capabilities, a model based approach is pursued to obtain this improvement. More specific, as a first main contribution, a new approach to control oriented modeling of gas/liquid (G/L) ILS is proposed which, in contrast to currently available such modeling approaches, allows for a comprehensive evaluation and design of G/L ILS control strategies. As an example application of the models resulting from this approach and as a second main contribution of this paper, a new model and feedforward control based method for fastly approximating the closed-loop performance limits of a G/L ILS is proposed. The motivation for pursuing this method is an acceleration in overall G/L ILS design speed. The merits of the method are demonstrated through a simulation based application on a commercially available G/L ILS.

Keywords: inline separation, oil and gas industry, slug control, model based control, feedforward control

1. INTRODUCTION

A current trend in the oil and gas (exploration & production) industry is to use compact –centrifugal forces based- so called inline separators (ILS) instead of their conventional voluminous -gravity based- counterparts to separate the multiphase flow (oil, gas and water) entering the surface. Motivations for that are the low cost, weight, volume and footprint of ILS systems, which render these particularly attractive for the increasingly important offshore, subsea and arctic applications.

Inline separators, see fig. 1 for an example of the gas/liquid (G/L) separation *c.q.* GLCC type (see e.g. Arpandi, Joshi, Shoham, Shirazi, and Kouba (1996) and Wang, Mohan, Shoham, and Kouba (2001)) create a 'swirl' in the flow to be separated to introduce the centrifugal forces necessary for separating the light from the heavy component. The resulting separation force ranges from *10g* up till even *3000g*, which is much larger than the *1g* separation force for gravity based separators. Inline separators are used for e.g. primary separation purposes, replacing their conventional vessel based counterparts, for secondary separation purposes, i.e. as an add-on to an already existing separator to enhance the total separation capacity, or for multiphase metering, with the separation allowing for more accurate flow measurements. See e.g. Kouba, Wang, Gomez, Mohan, and Shoham (2006) for field application examples, which number is steadily growing.

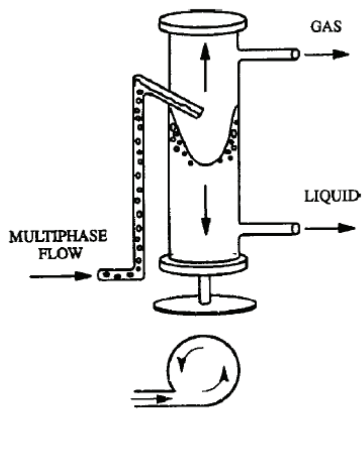

Fig. 1. The gas/liquid cylindrical cyclone (GLCC).

The main operational aims of ILS are (i) to fulfill certain *a priori* specified separation requirements, (ii) to keep the downstream pumps and compressors within a proper operating range (preventing e.g. cavitation or surge) and (iii) to fulfill safety regulations, which all have to be fulfilled in the presence of a variety of inlet flow variations typically present in oil, water and gas pipelines. With respect to the first of these requirements it is important to note that ILS do not fully separate the components. Rather, some of the light component always comes along with the heavy component and/or vice versa.

A problem with ILS is their high sensitivity towards inlet flow variations, which is caused by their small storage volume. This sensitivity lowers the effectiveness and efficiency of these separators and downstream pumps and compressors and easily causes operational problems and economic loss. These problems are amplified by an increasing number of production operations with significant flow variations due to slug flow pipeline conditions, which is a flow regime characterized by alternating liquid slugs and gas surges. Causes for these slug flow conditions are, amongst others, ageing of the wells, where the slug flow regime is entered due to a decreasing reservoir pressure and resulting decreasing flow rates, and the geometry of the pipeline, in particular the presence of elevated parts in the pipeline (e.g. the *riser* from sea bottom to offshore platform).

One way to reduce the ILS sensitivity towards inflow variations, and thereby towards the corresponding operational problems and economic loss, is via improved control. Here, motivated by the industrial need for cost-effective compact separators with sufficient inflow variation handling capabilities, a model based approach is pursued to obtain this improvement. More specific, as a first main contribution, a new approach to control oriented modeling of G/L ILS is proposed, which typically form the first stage in the overall separation train. The models obtained with this approach can be used for comprehensively evaluating conventional G/L ILS control strategies and designing new ones, i.e. taking *all* variables relevant for G/L ILS control into account rather than only part of these. Here, as an example application of the models resulting from this approach and as a second main contribution of this paper, a new model and feedforward control based method for fastly approximating the closed-loop performance limits of a G/L ILS is proposed, i.e. the range of slugs that still can be handled properly by the (controlled) G/L ILS. The motivation for pursuing this method is an acceleration in overall G/L ILS design speed. The merits of the latter method are demonstrated through a simulation based application on a commercially available G/L ILS, more specific on the GLCC (see fig. 1).

The contents of this paper are as follows. First, the control oriented G/L ILS modeling approach is outlined and discussed in more detail through an application involving the GLCC. Then, a straightforward model based method for assessing the closed-loop performance limits of a G/L ILS is presented. After that, a feedforward based adaptation of this method is proposed that allows for an accelerated overall G/L ILS design. Subsequently, the merits of the proposed method(s) are demonstrated through the mentioned simulation based application on the GLCC. At the end, a summary is provided of the main conclusions of this paper.

2. CONTROL ORIENTED MODELING OF GAS/LIQUID INLINE SEPARATORS

2.1 Aim

The aim of the proposed modeling approach is to derive a (relatively) simple yet sufficiently accurate model of the dynamics connecting, on one side, the manipulated variables (MVs) of a G/L ILS and its control-relevant disturbance variables (DVs) with, on the other side, its controlled variables (CVs). In this paper, the focus is on the GLCC type of ILS, in which case the MVs, DVs and CVs typically are as schematically depicted in fig. 2.

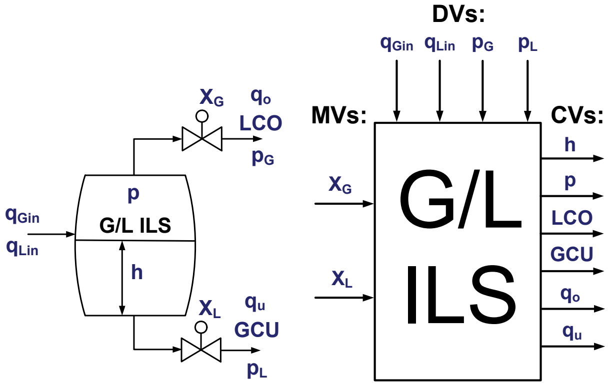

Fig. 2. Control relevant view on the GLCC.

Here, X_G denotes the opening of the overflow *c.q.* (predominantly) gas valve, X_L the opening of the underflow c.q. (predominantly) liquid valve; h represents the liquid level of the available (small) fluid storage capacity *c.q.* in the vertical cylinder; p its pressure; *LCO* the volume fraction of liquid coming along with the gas at the overflow valve, referred to as 'liquid-carry-over', *GCU* the volume fraction of gas coming along with the liquid at the underflow valve, referred to as 'gas-carry-under': these are the variables that quantify the separation (in)efficiency of the G/L ILS; q_o is the total volumetric flow rate through the overflow valve, q_u its underflow counterpart; q_{Lin} is the volumetric liquid inlet flow rate to the G/L ILS and q_{Gin} its gas counterpart: these are the main DVs. p_G resp. p_L, represent the pressures at the outlets of the over- and underflow valves and are also DVs.

2.2 Main idea

The main idea behind the proposed new control oriented G/L ILS modeling approach is based on the following two observations made from the literature on modeling such separators:

- The control oriented G/L ILS models available in the literature, which essentially are overall mass balances (see e.g. Wang et al. (2001)), contain all variables mentioned above as in- or outputs *except for GCU and LCO*, despite their high relevance for G/L ILS control. Rather, these models implicitly assume complete separation, i.e. zero *LCO* and *GCU*.

- Often, steady-state models describing the G/L ILS separation efficiencies, here referred to as *efficiency curves*, are available which *do* contain *GCU* and *LCO* as outputs or allow for the computation of these quantities. Such models are obtained through e.g. mechanistic modeling (e.g. Arpandi et al. (2001)) or empirically (e.g. Verbeek (2010)).

The main and straightforward idea behind the proposed modeling approach, now, is to combine, for some G/L ILS to be modeled, the available efficiency curves with an easily derived or already available (no *LCO* and no *GCU*) control oriented model of this G/L ILS, i.e. with overall mass balances for this separator, to form a single comprehensive control oriented model (incl. *LCO* and no *GCU*). The errors made by considering steady-state efficiencies rather than dynamic ones are assumed to be negligibly small, which is motivated by the assumption that the separation takes place at a faster pace than the accumulation(s) of liquid and gas. As a more detailed elaboration of the proposed modeling approach, it is applied now to model a GLCC.

2.3 Application to the GLCC

For reasons of space, the GLCC model is not discussed in full detail. Rather, only its global structure and main equations are outlined here. It is noted that the model still needs to be validated on real-life data and, hence, may still contain significant deviations from reality. However, at least for the purpose of presenting the main results of this paper it is considered to suffice.

Efficiency curves. The efficiency curves employed by the model here are as depicted in fig. 3 *c.q.* are of the form

$$\begin{aligned} LCO &= f_{LCO}(F_R, C_{in}) \\ GCU &= f_{GCU}(F_R, C_{in}) \end{aligned} \quad (1)$$

with

$$F_R = \left(q_o / (q_o + q_u)\right) / C_{in} \quad (2)$$

the so called *normalized flow split* and with

$$C_{in} = (q_{Gin} / (q_{Lin} + q_{Gin})) \quad (3)$$

the gas volume fraction at the inlet. These efficiency curves have not been derived from a GLCC but are translations of curves experimentally obtained from another ILS discussed in Verbeek (2010). At least for the purpose of presenting the main results of this paper, these curves are considered to suffice The *LCO* efficiency curve $f_{LCO}(.)$ reflects the phenomenon typically encountered at ILS that the ratio between the heavy (liquid) and light (gas) flow at the overflow valve (*LCO*) increases, i.e. in addition to the light flow itself, when the total overflow (q_o) increases relative to the total underflow (q_u). Hence, it quantifies the effect that opening the overflow valve or increasing the pressure drop over this valve results not only in more gas flow but also in more liquid flow through this valve. Vice, versa, the *GCU* efficiency curve $f_{GCU}(.)$ reflects the phenomenon typically encountered at ILS that the ratio between the light (gas) and heavy (liquid) flow at the underflow valve (*GCU*) increases, in addition to the heavy flow itself, when q_u increases relative to q_o. The value of q_u relative to q_o is quantified through F_R albeit in a normalized way through C_{in} (see eqn. (2)). This variable is an important variable from an ILS operation point of view. More specific, when $F_R>1$, the GLCC is in *degassing* mode, which is characterized by a relatively high total flow and high gas flow through the overflow valve, a low *GCU* but also a high *LCO*. As the name suggests, this operation mode refers to the main aim of removing the gas from the incoming multiphase flow. Vice versa, when $F_R<1$, the GLCC is in *deliquidizing* mode, with a relatively high total flow and high liquid flow through the underflow, a low *LCO* but also high *GCU*. Operation at $F_R=1$ is more suited for multiphase metering as this value implies that at steady-state $q_o = q_{Gin}$ and $q_u = q_{Lin}$, as can be derived from eqns. (2) and (3). Here, the focus is on deliquidizing and degassing operation applications.

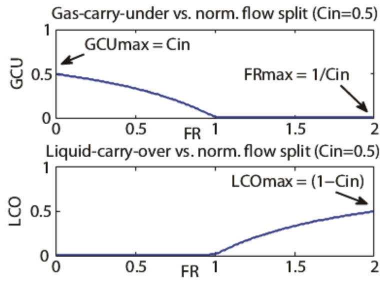

Fig. 3. Modeled GLCC efficiency curves.

The efficiency curves (1) are implemented in the model such that the corresponding values for *LCO* and *GCU* determine the amount with which each of the inflows q_{Lin} and q_{Gin} are separated in a part going to the upper part of the GLCC, referred to here as the *G* part as it is predominantly gas, and in a part going to the lower, here so called *L*, part:

$$\begin{aligned} q_{Lin} &= q_{Lin2L} + q_{Lin2G} \\ q_{Gin} &= q_{Gin2L} + q_{Gin2G} \end{aligned} \quad (4)$$

The overall result is a set of equations

$$(q_{Lin2G}, q_{Lin2L}, q_{Gin2G}, q_{Gin2L}) = f(q_u, q_o, q_{Lin}, q_{Gin}) \quad (5)$$

Mass balances. To each of the four flows q_{Lin2G}, q_{Lin2L}, q_{Gin2G} and q_{Gin2L} a storage volume V_{LinG}, V_{LinL}, etc., a volume fraction C_{LinG}, C_{LinL}, etc. and a mass balance is allocated. The outflows for these four mass balances are the corresponding liquid and gas parts of the under- and overflow q_u resp. q_o, denoted here as q_{Lo}, q_{Go}, q_{Lu} and q_{Gu}. Assuming the liquid phases to be incompressible, using the non-ideal gas law for the gas phases and approximating the pressure in the *L* phase by a height average value, the mass balances are straightforwardly derived, e.g. for the liquid-in-L phase as

$$\frac{dV_{LinL}}{dt} = q_{Lin2L} - q_{Lu} \quad (6)$$

Valve dynamics. For the GLCC valve equations simplified yet similar expressions of those used in Wang et al. (2001) are employed:

$$q_u = f(X_L)\sqrt{p + \rho_L g h - p_L}$$
$$q_o = f(X_G)\sqrt{p - p_G} \qquad (7)$$

Additionally, the model contains descriptions of lags and delays introduced by e.g. the presence of pneumatic transmission lines (see Wang et al. (2001)).

The flows q_{Lu}, q_{Go}, q_{Lo} and q_{Gu} at the valves are assumed to be proportional to corresponding volume fractions and are computed as $q_{Lu}= q_u\, C_{LinL}$, $q_{Go}= q_o\, C_{GinG}$, etc.

Pressure and liquid level. Pressure is computed as the pressure of the gas-in-G phase and is straightforwardly derived from the mass balance for this phase and the non-ideal gas law. Liquid level is computed from the relation

$$V_h = V_{LinL} + \mu_1 V_{GinL} + \mu_2 V_{LinG} = \left(\frac{\pi}{4}\right) d^2 h \qquad (8)$$

i.e. as a function of all available volumes except V_{GinG}, with the fit parameters μ_1 and μ_2 quantifying the contributions of these volumes. d is the GLCC (inner) cylinder diameter.

3. A METHOD FOR ESTIMATING G/L ILS PERFORMANCE LIMITS

A relevant question for the design of a G/L ILS is whether the expected range of inflow conditions (in particular slugs) can be handled by this separator. The answer to this question determines e.g. whether a larger ILS must be chosen or whether a slug mitigation device must be added (upstream). This answer can be obtained by computing the range of inflow conditions that (still) can be handled by the considered (feedback controlled) G/L ILS and comparing it to the expected range. A straightforward and model based method proposed here for determining this feasible range of inflow conditions is:

- Derive a control oriented model of the considered G/L ILS using e.g. the approach of section 2.
- Parameterize the inflows, e.g. by means of the simplified representation of fig. 4 with characterizing parameters A1, A2, T1, T2 and τ (time constant of unit gain first-order filter).
- Implement the considered (feedback) control strategy on the G/L ILS model.
- Specify the limits that determine the proper G/L ILS operation range, e.g. upper constraints on *LCO*, *GCU*, *h* and *p*.
- Vary each of the inflow characterizing parameters with the other parameter values held constant until a constraint is violated in the resulting closed-loop simulation.

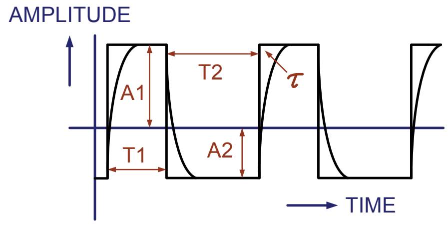

Fig. 4. Simplified slug representation.

- Draw plots or make tables containing the parameter values that correspond to a just-presence (or just-absence) of a constraint violation.

The final result is one or several plots or tables with inflow parameters that represent the boundaries of the range of manageable inflow conditions. Comparing this range of inflow conditions with its expected counterpart provides the answer to the G/L ILS design question posed here.

4. ACCELERATED G/L ILS DESIGN VIA FEEDFORWARD CONTROL

G/L ILS design can be accelerated by means of adaptations to the performance limits assessment method presented above. A first such adaptation is to use a simplified parameterization of the inflows, i.e. with as few parameters as possible. Additionally, this acceleration can be established through performing the assessment method in the early stage of the G/L ILS design process with the (feedback) control strategy actually to be implemented replaced by a control strategy that

- is easier to implement and faster to simulate than the control strategy actually to be implemented
- outperforms the latter control strategy *c.q.* is able to handle much larger inflow variations than the control strategy actually to be implemented

By using this faster, easier-to-implement and outperforming control strategy in the first stage of the design process one is able to determine in a fast manner whether the considered G/L ILS is able to handle the expected range of inflow conditions *anyway*, i.e. at least when optimally controlled. Here, the fact is exploited that the substituting control strategy allows for a larger range of manageable inflow conditions than the control strategy actually to be implemented. Hence, if this larger range is already smaller than its expected counterpart, one does not need bother to investigate the range corresponding to the control strategy actually to be implemented and a re-design or slug mitigation device should be considered. If not, one can make a refinement step and perform the proposed performance limits assessment method with the control strategy actually to be implemented to find out if the considered G/L ILS is truly able to handle the expected range of inflow conditions. As the latter approach is not followed directly from the start of the design process, a significant acceleration of this process may be obtained.

It remains to be answered what could be used as the substituting faster, easier-to-implement and outperforming G/L ILS control strategy. The answer to that question proposed here is a steady-state feedforward (FF) control strategy that has the same control objectives as the feedback (FB) control strategy under consideration. Such a FF control strategy can be shown to be generally exhibit a much better control performance than its FB counterpart, even though it is sub-optimal from a FF point of view (due to neglecting dynamics). This much better performance is due to a much faster convergence to the final optimal steady-state, which can be subscribed to the immediate implementation of the corresponding optimal steady-state MVs and to the fast dynamics of the G/L ILS. FB control strategies converge much slower to the optimal steady-state due to the presence of lags and delays in the valves and due to the (PID) time constants of the FB control strategy itself.

More specific, it is proposed to equip the FF control strategy with the ability to compute a steady-state solution that (i) balances the in- and outflows of the GLCC and that (ii), through inversion of the considered efficiency curves, is optimal from the point of view of the corresponding separation efficiency objectives. This allows for minimal variations in the G/L ILS CVs and for close-to-optimal tracking of the optimal separation efficiency, which are the main aims of a G/L ILS.

To elucidate the proposed FF strategy, the layout of such a strategy is provided here for a GLCC which dynamics follows that of the model of section 2. This GLCC-FF control strategy proceeds as follows:

- *A priori* specification of a setpoint for either *LCO*, *GCU* or F_R. This setpoint defines the optimal operating point from a separation efficiency point of view and is to be maintained by the FF strategy.
- Retrieve the current values for q_{Lin} and q_{Gin}
- In case a setpoint is specified for either *LCO* or *GCU*: usage of the F_R-*LCO* or F_R-*GCU* efficiency curve to compute the corresponding setpoint for F_R.
- Computation of the setpoints for q_o and q_u for given setpoint for F_R using the expression (2) for F_R and the fact that in steady-state $q_u+q_o=q_{Lin}+q_{Gin}$. Incorporation of the latter expression causes the fast balancing of GLCC mass balances and, thereby, minimal variations in its CVs.
- Computation of the setpoints for X_L and X_G from those for q_o and q_u, using valve eqns. (7) and known or approximated values for h, p, g, ρ_L, p_L and p_G.

See fig. 5 for a schematic view of the proposed FF strategy. The choice of setpoint here depends on the mode of operation chosen for the GLCC. When choosing the degassing mode of operation in terms of aiming to always operate at a maximum gas flow through the overflow valve q_{Go}, a suitable choice of setpoint is one for *LCO*. More specific, a suitable setpoint for this operating mode is the upper limit LCO^{max} on this variable to avoid operational problems for downstream equipment like compressors. The reason for that is that at the corresponding operating point q_{Go} is at its maximum, i.e. without violating LCO^{max}: $q_{Go}=q_{Go}^{max}=LCO^{max}q_o^{max}$, with q_o guaranteed to be maximal (without exceeding LCO^{max}) due to (i) the monotone-increasing property of the F_R-*LCO* efficiency curve (see fig. 3), resulting in $F_R=F_R^{max}$ for $LCO=LCO^{max}$, and due to (ii) $q_o= q_o^{max}$ for $F_R=F_R^{max}$, as can be derived from the definition of F_R (eqn. (2)).

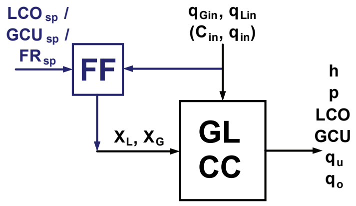

Fig. 5. Schematic view of GLCC FF strategy.

Note the simplicity, low numerical complexity and relatively easy implementation of the GLCC-FF strategy (most complexity lies in the inversion of the F_R-*LCO* or F_R-*GCU* efficiency curves. Also, no tuning is required). The merits of this strategy and the proposed G/L ILS performance limits assessment method are now demonstrated on a simulation based application involving the GLCC.

5. APPLICATION

5.1 Case definition

Consider a GLCC with diameter *0.1 [m]* and height *3 [m]* that is to be used for degassing operation with $LCO^{max}=0.15$ and $GCU^{max}= 0.08$ using a FB control strategy with the aims of maintaining the *LCO* setpoint at LCO^{max} and keeping the variation in h and p to a minimum. Although not further elaborated here, it can be shown that this can be established by means of a master *LCO*- & slave *h-p* PID cascaded control strategy. Other operation limits are not present or do not matter for the application here. Also, assume that the considered GLCC can be accurately modeled by the model discussed in section 2. Further, assume that it is estimated that operation of this GLCC is expected to have to handle slug type of variations in C_{in} around an average value of *0.5* with amplitudes up till A=A1=A2=*0.25[-]*, periods T=T1=T2 between *0.5* and *10 [s]* and with τ=0, while the total gas inflow q_{in} is assumed to remain constant. The question that is to be answered is whether the considered GLCC, in closed-loop operation, is up to this task or that, alternatively, a larger GLCC needs to be chosen or some slug mitigation device needs to be added. As a first step in answering this question, the GLCC-FF control strategy discussed above is employed, which has the same objectives as the FB control strategy considered here, to determine in an early stage and in a fast manner whether the imposed limits can be met anyway.

5.2 Results

A simulation result obtained with the application of the proposed FF control strategy is depicted in fig. 6 (solid blue line), where a slug of width T=*2 [s]* is applied, at first with amplitude A=*0.12* and then, from approx. *time=20 [s]*, with amplitude A=*0.25*: see the plot for C_{in}. As can be observed from this figure, the constraint on *GCU* is hit by slugs with amplitude A=*0.25* whereas the G/L ILS remains within the proper operational range for slugs of amplitude A=*0.12*. Note that the *LCO* setpoint is maintained very well by the FF strategy. Also, results obtained with the considered *FB* control strategy are depicted. Note the (expected) much worse performance.

Repeating these simulations for other periods T within the range of *0.5-10 [-]* leads to the results depicted in fig. 7, where upper limits on A are depicted as a function of T below which GLCC operation is still within the acceptable or expected range.

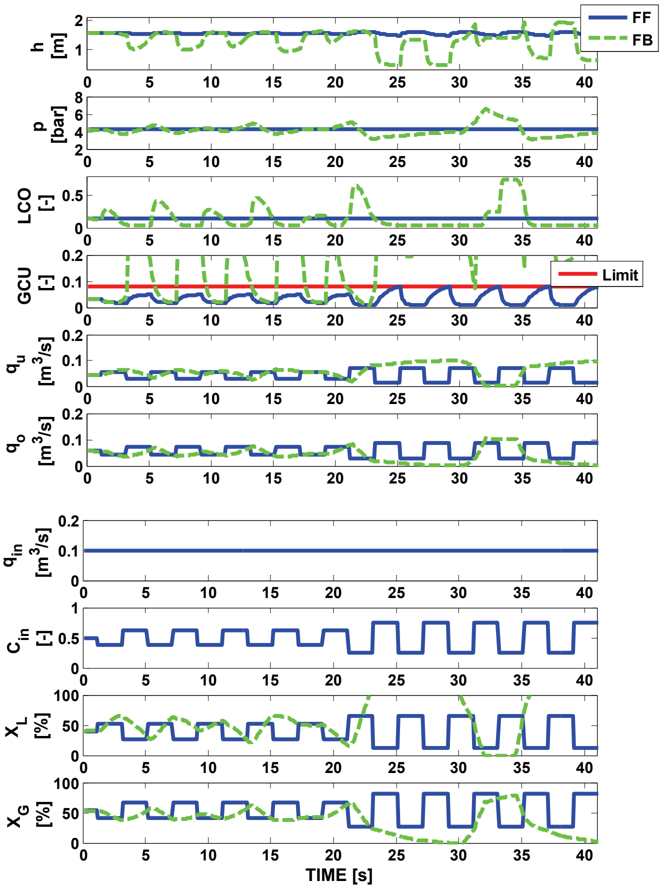

Fig. 6. Feedforward GLCC control: CVs, MVs and DVs.

It is noted that up till T≈*1.5 [s]*, the dominating constraints are the upper and lower limits of *100* resp. *0 [%]* on X_L and X_G whereas for T larger than *1.5 [s]* GCU^{max} is the dominating constraint. From this plot it is observed that it is not possible to fulfill the specs on the inflow conditions with the considered GLCC as for T>*2 [s]* the expected upper bound on the amplitude A exceeds the upper bound reachable with the GLCC. Hence, one needs to choose a larger GLCC or add some slug mitigation device.

Fig. 7 also depicts the range of inflow conditions manageable in open-loop operation. As one can see, this is a much smaller range than reachable with the GLCC in FF controlled operation, which indicates the large improvement in slug handling capacity that can be obtained when applying an optimal ILS control strategy.

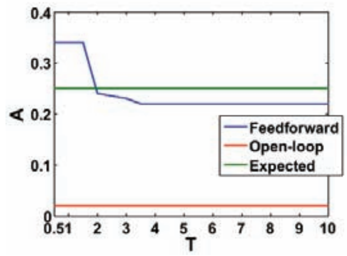

Fig. 7. Manageable and expected range of flow variations.

6. CONCLUSIONS

Motivated by the industrial need for cost-effective compact separators with sufficient inflow variation handling capabilities, a model based approach is pursued here to obtain a substantial improvement in G/L ILS control performance. More specific, as a first main contribution, a new approach to control oriented modeling of G/L ILS is proposed. The models obtained with the approach can be used for comprehensively evaluating conventional G/L ILS control strategies and designing new ones. As an example application of the models resulting from this approach and as a second main contribution of this paper, a new model and feedforward control based method for fastly approximating the closed-loop performance limits of a G/L ILS is proposed. This method allows for a significant acceleration of overall G/L ILS design speed. The merits of the method are demonstrated through a simulation based application on a commercially available G/L ILS.

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REFERENCES

Arpandi, I.A., Joshi, A.R., Shoham, O., Shirazi, S.A. and G.E. Kouba (2001). Hydrodynamics of two-phase flow in gas/liquid cylindrical cyclone separators. *SPE Journal*, **1**, 427-436, SPE 30683.

Kouba. G., Wang, S., Gomez, L., Mohan, R. and O. Shoham (2006). Review of the state-of-the-art gas/liquid cylindrical cyclone (GLCC) technology - field applications. In: *Proc. SPE Int. Oil & Gas Conference and Exhibition,* Beijing, China, SPE 104256.

Verbeek, P. (2010). Personal communication.

Wang, S., Mohan, R.S., Shoham, O. and G.E. Kouba (1996). Dynamic simulation and control-system design for gas/liquid cylindrical cyclone separators. *SPE Journal*, **6**, 236-247, SPE 71308.