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Original Article

A water treatment case study for quantifying model performance with multilevel flow modeling

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ABSTRACT

Decision support systems are a key focus of research on developing control rooms to aid operators in making reliable decisions and reducing incidents caused by human errors. For this purpose, models of complex systems can be developed to diagnose causes or consequences for specific alarms. Models applied in safety systems of complex and safety-critical systems require rigorous and reliable model building and testing. Multilevel flow modeling is a qualitative and discrete method for diagnosing faults and has previously only been validated by subjective and qualitative means. To ensure reliability during operation, this work aims to synthesize a procedure to measure model performance according to diagnostic requirements. A simple procedure is proposed for validating and evaluating the concept of multilevel flow modeling. For this purpose, expert statements, dynamic process simulations, and pilot plant experiments are used for validation of simple multilevel flow modeling models of a hydrocyclone unit for oil removal from produced water.

1. Introduction

Decision support systems are crucial in attempts to improve the efficiency and safety of control systems. With an increase in system complexity and autonomy, tasks for operators to analyze situations to determine behaviors that deviate from nominal system operation are becoming increasingly complicated. Automated fault diagnosis is a method that can potentially decrease the reaction time and increase the probability of correct responses to faults. The focus of online fault diagnosis has primarily been at the component level. Multilevel flow modeling (MFM) is a method for modeling the functionality of complex mass and energy flow systems. The method is used to model how low-level functionality supports high-level functionality, commonly referred to as means-end modeling. Models of nuclear power systems, electric power grids, and oil production systems have been used for online fault diagnosis [1].

MFM has numerous different applications, of which online fault diagnosis is one. Online fault diagnosis with MFM is, however, limited in application [1–6], whereas offline root cause analysis has been applied diversely. Current methods for model validation of MFM models are limited in application, as the models primarily have been used for offline root cause analysis. The models must be reliable if they are to be used for online fault diagnosis in industrial decision support systems. Insufficient validation of models to improve decision reliability may prove to be counterproductive when seeking to improve the level of safety.

No additional requirements are defined for advanced or intelligent control algorithms or for diagnostic methods in standards as NORSOK I-002 on Safety and Automation Systems [7]. In cases of false or absent alarms and diagnoses, operators may eventually ignore decision support systems and solely rely on their own experience and intuition. In line with the concept of defense in depth [8], fault diagnosis is used as an addition to the monitoring level, at level 2, to enable either prevention or mitigation of faults. To the same degree as an emergency shutdown, a fault diagnostic system should thus be considered a safety precaution, although its function according to the defense in depth concept is at a different level. Model validation and testing is thus crucial.

This article introduces initial work on an approach to validate MFM models based on different types of available information. It has been applied to simple MFM models of a deoiling hydrocyclone. The aim is to provide a measure of model performance.

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2. Previous validation

MFM is a strictly qualitative method. Numerical process signals are used but only to produce qualitative and discrete states such as low, normal, or high. The states are then processed by the MFM reasoning in combination with the MFM model. The discrete states simplify the rule base and thus the reasoning process, significantly, and ensure low computational effort when dealing with plant-wide fault diagnosis [1]. Systems have typically been modeled and validated by an expert in MFM and a process expert. Based on the model, functions are triggered separately, and the prognosis is compared to the causes and consequences as explained by a process expert. Alternatively, an MFM and/or a process expert attempts to describe how the MFM prognosis relates to the dynamics of the process system. This approach is subjective and qualitative. In addition, it introduces bias to the validation, as there is no distinction between the input used to build the model and that used to validate it.

The majority of published research on the topic of MFM is not concerned with the validity of the models. This is very problematic, as many models are presented with no information on how well they model the physical system. The published research addressing validation includes examples of comparisons of expert statements to cause consequence fault trees, to counter actions generated based on MFM model prognoses, and to fault trees published in scientific literature [9–11]. More recently, model prognoses have been compared to standardized operation procedures available in published standards, and to numerical process simulations [12]. The standardized operation procedure and MFM prognoses were presented in a table for easy comparison as a basis for a qualitative evaluation [13]. In addition, different theoretical aspects of MFM model validation are discussed in the study by Wu et al. [14]. All the previously mentioned approaches focus on the validity of the model according to the output produced by a specific input. Causal relations between functions have been discussed by Larsson et al. and Berquist et al., and a correlation method was presented to determine the causal relationship between functions [15,16]. The validity of the causal relationship is the only example of validation of the structure of MFM models. Apart from this, the structure is only treated as a part of the verification, according to a defined MFM syntax [14].

3. Hydrocyclone

The validation method is demonstrated using a simple case study of hydrocyclone equipment for water treatment. A hydrocyclone is a passive component used for separation of water and oil in offshore Produced water treatment (PWT). It has one inlet and two outlets. If the process conditions are optimal, the oil dispersed in the water leaves the hydrocyclone through the overflow outlet and the treated water leaves through the underflow outlet, as shown in Fig. 1.

The common control strategy is based on the pressure drop ratio (*PDR*), defined as the ratio of the pressure difference from inlet to overflow ΔP_o to that from inlet to underflow ΔP_u as shown in Eq. 1 [18].

$$PDR = \frac{\Delta P_o}{\Delta P_u} = \frac{P_i - P_o}{P_i - P_u} \tag{1}$$

As the density of water is higher than that of oil, the centrifugal force of the water exceeds the centrifugal force of the oil particles. The inlet flow enters tangentially into the conical geometry of the hydrocyclone, thus passively generating a rotational flow. This results in the water moving outwards, toward the hydrocyclone wall, in a vortex; the oil is displaced toward the center of the hydrocyclone, in a vortex.

The separation efficiency of the hydrocyclone does not only depend on the *PDR* but also on the flow split F_s, inlet flow rate, oil content, oil droplet size, and geometry. The flow split is proportional to the *PDR*, and it can be defined as the ratio between the overflow flow rate Q_o and the input flow rate Q_i [17]:

$$F_s = \frac{Q_o}{Q_i} \tag{2}$$

The *PDR* is controlled using two control valves, one at each outlet. A P&ID of the hydrocyclone used for experimental work is shown in Fig. 2. The setup has a pressure and a flow rate sensor on all inlets and outlets and one control valve on each outlet. The input water is delivered from a water tank by a pump. Both the underflow and overflow outputs are transported to the same water tank.

The standard offshore application of hydrocyclones involves upstream separation, in combination with three-phase separation tanks. The underflow valve is then used to control the water level in the three-phase separation tank, and the overflow valve controls the PDR. In this application, any other processes besides the hydrocyclone are bypassed, and the underflow valve has no real-time control. In a standard application, the hydrocyclone is placed in a bundle of hydrocyclones, among which the inlet water is divided. This is however not the case in this particular application, in which only a single hydrocyclone is used.

4. MFM model

As a case study, only a part of the full MFM model of the hydrocyclone will be used to prove and present the principle of this validation method. This part is the mass flow, shown in Fig. 3. As can be seen in the figure, there are six transport functions, of which three represent the three flow rate sensors and three storage functions representing the pressure sensors. A balance function represents the mass balance of flow from the inlet to the underflow and the overflow.

The model shown in Fig. 3 can potentially be used in two different models, by having two different representations of the sensors. The mapping from component to function will thus be the only difference between the two models: v1 and v2. The MFM models and their respective mappings are shown in Table 1. The third model, v3, is similar to v2, but the causal relation in2 has been

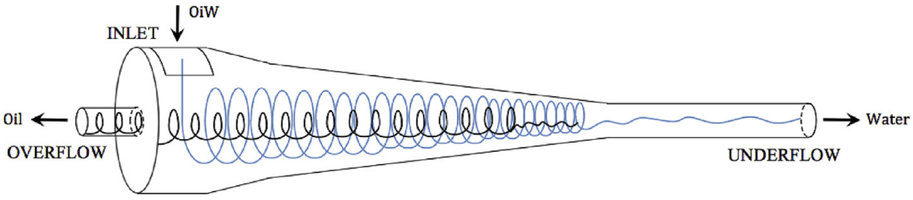

Fig. 1. Example of water and oil flow in a hydrocyclone [17].