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MONITORING LEAKAGES ON OIL PRODUCTION OFFLOADING AT OPEN SEAS USING STATISTICS ASSOCIATED WITH MASS BALANCE METHODS

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ABSTRACT

With the increasing number of former VLCC (Very Large Crude Cargos) transformed into FPSOs worldwide, and its associated inherent oil production exportation characteristics to shuttle tankers, where very large flow rates are combined to the use of short and large diameters exporting lines, in many cases involving the use of hoses instead of flexible pipelines, and the obviously very sensitive environment, considering the execution of this transference in open seas, where losses for even a small period, regarded the involved exportation capacity means a huge spillage, with all its legal and image associated impacts, the challenge to identify and test technologies able to carry out the most effective leakage detection in this scenario was placed to PETROBRAS technical team, as consequence of rules demanding the installation of such systems stated by Brazilian Environmental Agencies.

The proposal of this paper is to show the leakage detection solution based on a hybrid method combining mass balance along with statistical treatment adopted for monitoring the oil production offloading from the FPSO - MARLIM SUL, in the Campos Basin, Brazil, to a dynamically positioned shuttle vessel throughout a 150 meters, 20" diameter hose designed for a flow rate of 8.000 m³ per hour.

A short description of this production system is provided, the operational principles of the adopted leakage system are depicted, its architecture is detailed, and the reasons that ended up leading PETROBRAS to adopt this technology amongst those others also considered are presented.

Finally, comments about the installation, start-up and tuning, and considerations about the system observed behavior are made.

Keywords: Leak Detection Systems; Pipeline Monitoring; Statistical Process Analysis.

INTRODUCTION

Many different technologies for leak detection in pipelines have been described in recent specialized publications. Industrial applications, mainly in petrochemical and oil & gas transportation industries have been implemented during last years. These applications can be classified according to their specificity such as if they are applied on offshore or onshore installations, for multi phase or single phase flow regimes, and depending on the technology they are based on. In this sense, available technologies may be grossly distributed in following groups: 1) compensated mass balance, based on the solution of the steady state set of equations which model a specific pipeline, known as RTM-Real Time Model; 2) Same as group 1, but solving the transient set of equations, known as RTTM-Real Time Transient Model; 3) Pressure wave behavior; 4) Statistical Modeling. Hybrids schemes can also be found. Extensive definitions of system performance and operational criteria for LDS systems for oil and gas industries are presented in API 1155 (1995) and API 1130 (1995).

Selecting one among these technologies may be the most important step when designing a LDS (Leak Detection System). In that phase these issues must be considered as well as the instrumentation availability.

For this application, the main conditions considered prior to selecting the LDS technology were: 1) Low incidence of false alarms; 2) High sensitiveness; 3) Single phase flow regimen; 4) Instrumentation availability. Being the main restriction to this application the absence of flow and temperature measurements on the discharge end; 5) Shuttle tankers are different from one transferring batch to another, what imposes that different instrumentation, process conditions and tuning parameters must be settled. For this, a defined number of pipeline models will be defined and self-tuned along operation cycles, each one composed by the FPSO with its pumps, instruments and hose plus a specified FSO, with its instrument features and process specificities. Considering these characteristics and restrictions, a hybrid model based on mass balance and statistics pattern recognition was selected. Technical details of this technology may be found in Zhang (1993, 1997, 1998), and two application cases are described by Zhang (2001) and Tindell & Zhang (2004).

NOMENCLATURE

FPSO – Floating Production, Storage and Offloading System

VLCC – Very Large Crude Cargo

LDS – Leak Detection System

SPRT - Sequential Probability Ratio Test

RTM - Real Time Model

RTTM - Real Time Transient Model

HYBRID MASS BALANCE AND STATISTICAL TREATMENT CONCEPTS

As described by Zhang & Di Mauro (1998), this scheme applies statistical techniques to detect changes in the overall behavior of flow and pressure at the ingress and egress points. Although the control and operation may vary from one pipeline to another, the relationship between the pipeline pressure and flow will always change after a leak develops in a pipeline. For example, a leak could cause the pipeline pressure to decrease and introduce a discrepancy between the ingress and egress flow-rate.

Leak determination is based on probability calculations at regular sample intervals. The basic principle used for the probability calculations is mass conservation and hypothesis testing: leak against no-leak. Although the flow and pressure in a pipeline fluctuate due to operational changes, statistically the total mass entering and leaving a network must be balanced by the inventory variation inside the network. Such a balance cannot be maintained if a leak occurs in a network. The deviation from the established balance is detected by an optimal statistical test method - Sequential Probability Ratio Test (SPRT).

Under leak-free operations, the mass balance principle determines that the difference between the ingress and egress flow-rate should be equal to the inventory variation in a pipeline. Therefore the following term is calculated:

$$\tau(t) = \sum_1^M Q_i(t) - \sum_1^N Q_o(t) - \sum_1^L \Delta Q_j(t) \quad (1)$$

where $\tau(t)$ is called the corrected flow difference term at time t . In practice $\tau(t)$ usually fluctuates around a non-zero value due both to the inherent differences in the instruments and fluid compressibility.

$Q_i(t)$ represents the flow measurement at the ingress points and $Q_o(t)$ at the egress points. M is the number of ingress points, N the number of egress points and L is the number of pipeline sections.

$Q_j(t)$ is a correction term for the inventory variation over the sample period of $t-1$ to t . $Q_j(t)$ is a function of pressure and temperature in the pipeline. Different product types in the network will introduce changes in the inventory calculations. The mean value of the above process $\tau(t)$ remains unchanged unless a leak develops in a pipeline or an instrument error occurs. The distinction between these two failure modes has to be made by further analysis, e.g. instrument change pattern identification.

To detect leaks efficiently with a low false alarm rate, SPRT will be used to decide between the leak-free and leak-present hypotheses, e.g.

H_0 : $\tau(t)$ is gaussian with mean m and variance σ^2

H_1 : $\tau(t)$ is gaussian with mean $m+\Delta m$ and variance σ^2

where m represents the mean value of $\tau(t)$ under normal (leak-free) operations and Δm is a parameter determined by the leak size to be detected. One example is shown in Fig. 1 below.

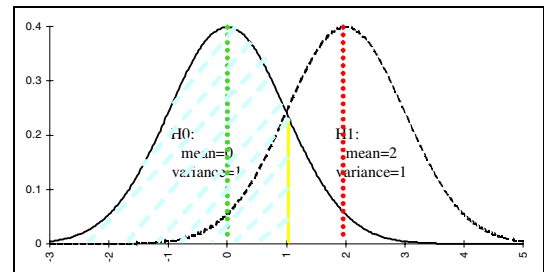


Figure 1: Leak-free x Leak test

To take into account of instrument drifts over time, m is tuned slowly using measurements available during a no leak alarm period. The value σ^2 depends on the fluctuations of the flow and pressure signals in a pipeline. For changing operating conditions in the pipeline, different values of σ^2 will be used. Usually three operating modes are identified automatically in a pipeline:

- Steady state operation, operating status = 0,
- Medium operational change, operating status = 1,
- Large operational change, operating status = 2.

After a large operational change, it will take longer for the system to detect a leak than during steady state operations. The choice of the different σ^2 values is determined to achieve maximum system reliability, without loss of leak detection functionality.

The SPRT for testing hypothesis H_1 against H_0 is

transformed to the calculation of the following cumulative sum:

$$\lambda(t) = \lambda(t-1) + \frac{\Delta m}{\sigma^2} \left(\tau(t) - m - \frac{\Delta m}{2} \right) \quad (2)$$

By comparing the on-line calculated value $\lambda(t)$ with a pre-set threshold value, a leak alarm can be generated.

After a leak is detected, the leak rate is estimated by subtracting the on-line updated value m from the average value of $\tau(t)$ shown in equation (1).

One key feature of the SPRT its learning capability, e.g. operational changes introduced after the installation may be used to further tune the system and gradual instrument drift may be incorporated for eliminating false alarms. The reliability of the system will improve after experiencing different operational changes such as start up, shut down and valve opening.

INSTALLATION DETAILS

FPSO - MARLIM SUL, located in the Campos Basin, Brazil, is a transformed VLCC equipped with a 150 meters long, 20" diameter hose designed for a flow rate of 8.000 m3 per hour. Through this hose the oil produced is transferred to a dynamically positioned shuttle tanker under low pressures and high flow rates.

The instrumentation, radio communication, SCADA and LDS systems, as well as security variables are presented in the Architecture diagram, shown at Fig. 1. At the hose inlet pressure, temperature and flow rate measurement are provided. At the other end, the delivery point located in the shuttle tanker, there is only one pressure transmitter. Important is to stress the absence of, flow and temperature monitoring. However, the selected LDS has an interesting capability of producing virtual instrument signals from dynamic models whose parameter can be learnt and tuned with process variables acquired along the time. This feature computes the very important flow sensor at the tail of this hose, and the inherent ability of this LDS to work without that was preponderant in the motivation for choosing this technology. However, due to the usage of this virtual flow meter, small increases in the minimum detectable leak rate and detection time (assuming the same level of false alarms), and possibly the level of false alarms for smaller leaks are expected and will be quantified during the tuning phase. Typically, for a pipeline like this, the minimum detectable leak with flow meters at both ends would be 2 times the repeatability of the flow meter, but for this case we are initially aiming for a 1% of flow rate detection, despite the repeatability of this flow meter be 0.2%. This may be revised to account to the particularities of this line and associated vessels.

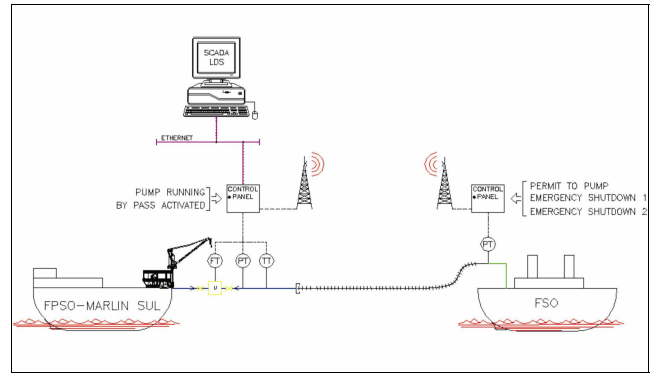


Figure 2: Architecture

Programmable logic controllers (PLC) at both ends control the pipeline and pumps operation providing security flags exchanged through a radio system. Specifically, in the shuttle tanker 3 digital signals are supplied. Namely:

- *Permit to pump*;
- *EDS1 – Emergency shutdown 1*, used to indicate that the pump must be turned off;
- *EDS2 – Emergency shutdown 2*, used to indicate that the pump must be turned off and the hose disconnected.

At the other end, in the FPSO node, the two implemented digital signals are:

- *Pump running*, used to indicate to LDS the start/stop of the oil transferring;
- *By-pass activated*, to indicate when, for any reason, the signal *Permit to Pump*, received from shuttle tanker is bypassed.

Two Motorola MOSCAD® RTUs (Remote Terminal Unit) equipped with analog and digital I/Os and radio modules are connected to the process signals and to PLCs at both FPSO and FSO ends. Through these equipments, the pressure signal and the 3 digital signals above described are transferred from the FSO to the MOSCAD® at the FPSO and from this, through MODBUS™, to the PLC in charge of controlling statuses and pumps operation.

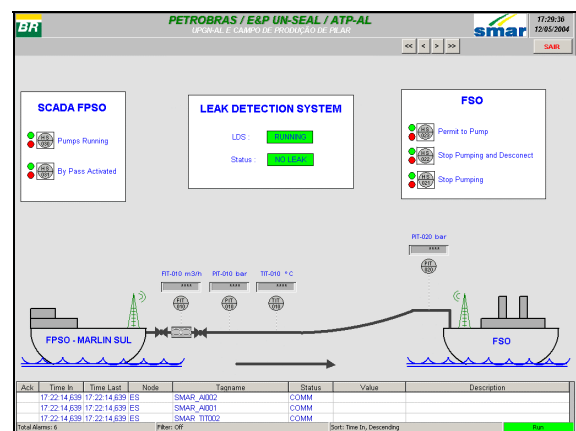


Figure 3: SCADA screen

As can be seen at Figure 2, at the FPSO the RTU is connected through an Ethernet module to the TCP/IP network. Also connected to this network is a workstation running MS Windows 2000™, installed to host both the SCADA and the LDS systems. From bottom to up, all discussed analog and digital signals go from the local RTU (which acquires data from the remote RTU, at FSO tanker) through the MODBUS/TCP protocol and reaches the *In Touch™* software, the SCADA system specified for this project. Operation personnel can monitor all variables coming from instruments and statuses of digital variables hosted by the PLCs on the synoptic screen designed and running on *In Touch™*.

Hosted by the same workstation is the Leak Detection System software, which receives information from PLCs through Ethernet MODBUS™ and sends its results to SCADA through Microsoft DDE (Direct Data Exchange). This software receives all pressures, temperatures and flow rates available as well as the Pump Running signal, all of them associated with their quality status. Due to the statistical nature of this LDS, all signals are sent to it without any filtering or pre-processing treatment, as it is supposed that important information could be lost otherwise. At each cycle, the LDS software updates its virtual flow rate sensor (the missing physical flow rate at FSO) and, after processing its models, sends back to SCADA through MS DDE statuses of operation, leak warnings and alarms. Handshaking between SCADA and the LDS software is also implemented generating alarms if any communication or software problem occurs.

This architecture enables the operator to monitor all process variables coming from the instrumentation, operation conditions from the control PLCs and statuses and alarms from LDS concentrated in a unique synoptic screen. All these variables are maintained in historical registers for further analysis.

Additionally, the LDS software provides more detailed graphical screens with its parameters and statuses to be used when more detailed information on the LDS is desired. Figure 4 shows one example of those screens.

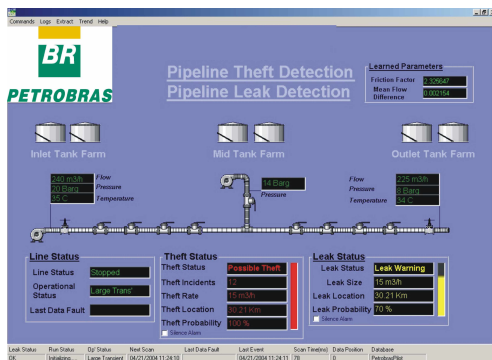


Figure 4: LDS software screen example

RESULTS

As long as this project isn't concluded yet, real results couldn't be extracted from field installation. Expected results calculated during the specification phase are shown in table 1.

Performance	Specific Performance Criteria	Operating Condition
Sensitivity	Minimum detectable leak rate not to exceed <u>1</u> %.	Steady State
Reliability	Incorrect leak declarations not to exceed <u>2</u> per year.	Overall
	Incorrect leak declarations not to exceed <u>2</u> per year.	Transient
	Incorrect leak declarations not to exceed <u>0</u> per year.	Steady State
	Incorrect leak declarations not to exceed <u>0</u> per year.	Start up
	Incorrect leak declarations not to exceed <u>0</u> per year.	Shutdown
Robustness	No loss of function due to 2 pressure outages.	Overall
	No loss of function due to all temperature outages.	Overall
	No loss of function due to <u>0</u> flow measurement outages.	Overall
	No loss of function due to pump state change.	Overall
Accuracy	Leak rate error not to exceed <u>1</u> %.	Steady state

Table 1: Expected performance of the system

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