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UNCERTAINTY QUANTIFICATION IN FLOW ASSURANCE APPLICATIONS THROUGH SURROGATE MODELLING APPROXIMATIONS

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ABSTRACT

Uncertainties in flow systems constitute an important factor in the design of such systems and so far their impact is assessed through purely qualitative techniques. Variables such as surface roughness, pressure drop coefficients, material and flow properties are just a few of the variables that cannot be deterministically modelled towards an optimized design. This paper investigates the reliability assessment of a simple one phase flow system and a two phase flow system, documenting the gradual development of an efficient methodology for estimation of resultant reliability throughout the system's service life. This methodology involves non-intrusive stochastic expansions together with advanced approximation techniques in order to accurately model the system under investigation.

Keywords: Pipeline Probabilistic Assessment, Surrogate Modelling, Dynamic Kriging.

INTRODUCTION

Quantification of uncertainties in flow systems constitutes a major issue towards operational optimization avoiding current over conservative design practice of safety factors application. Temperature, pressure, flow rate, flow regime, roughness, heat transfer coefficients are indicative design variables characterised by stochasticity. Appropriate consideration of the effects of uncertainty is essential towards a better understanding of the service life performance degradation of such systems.

Qualitative or semi-quantitative methods are mainly used for flow assurance problems providing valuable information for the risks inherent in the design, however quantitative methods should be more widely applied for more robust designs. Methods used heavily depend on historical data and experts opinions. Such techniques include Reliability, Availability and Maintainability (RAM), Reliability-Centred Maintenance (RCM), Failure Mode Effects (and Criticality) Analysis (FMEA, FMECA) and Fault Tree Analysis (FTA). Some initial studies of quantitative assessment were presented by Edwards et al. (1996), and Oliver and John (2007).

Large scale offshore pipelines, mainly for the Oil & Gas industry, is a typical example of a system subject to uncertain conditions with corrosion impact estimation being a major issue in the operability of piping systems. To this end extensive literature is available for the estimation of pipe wall corrosion and reliability and safe operability assessment of worn out pipes using inspection data as found in (ASME, 2002), (Bai et al., 1994) and (Belov et al., 2011).

This paper aims to present the sequential development of an efficient methodology for the quantitative assessment in flow assurance problems allowing a better understanding of its service life performance. The methodology that is documented and is subsequently applied initially for validation in a single-flow and then extended in a two-phase flow system. It considers both direct numerical simulations and various approximation methods, comparing them in terms of computational time and accuracy in the results.

RISK ANALYSIS IN FLOW ASSURANCE SYSTEMS

Currently design of flow systems is governed by relevant standards, indicatively the ones published by BSI (2012) and European Committee for Standardization (2011). Additionally common practices following the Allowable Stress or Limit State Design approach and considered geophysical pipeline location are used during the design. The main failure modes considered in these design codes are burst pressure and external collapse. Many other failure modes are not considered during design and in order to assess their impact on the safety of the system, the aforementioned qualitative techniques are often employed. Causes of failure can be identified in internal and external corrosion, off-design operational conditions, unpredicted events, faulty pipe material, poor welding, poor maintenance, fatigue and fracture, buckling, puncture, overload to name a few.

This practice ensures systems that meet minimum levels of safety however do not allow a systematic assessment of their real-time performance or optimisation of design requirements of individual components, due to the presence of various sources of uncertainty. Elimination of the latter constraint following a reliability assessment approach would allow, further to design, also operational optimization of a flow system estimating the remaining time to failure and hence allowing a planned rather than unplanned maintenance operation.

METHODS FOR QUANTITATIVE RELIABILITY ASSESSMENT

Quantitative reliability assessment (QRA) has been successfully applied in the past in problems of structural engineering especially in cases of critical infrastructure of nuclear, aerospace or civil engineering applications. Typically input of a QRA is a series of stochastic variables and their corresponding distributions together with an expression that describes the response of this system under the effect of these variables. In simple problems these expressions might be analytically derived while in more complicated ones, approximation methods may need to be employed generalizing results from a few deterministic simulations. The latter constitutes non-intrusive approaches, as illustrated in Figure 1, and are the ones that this paper adopts.

Fig.1 Non-intrusive methods

Design matrix should consider the appropriate number of design point so that the response surface is adequately represented in the design space (Gavin and Yau, 2008). Employment of non-intrusive methods allows use of specialized tools and hence preparation and execution of simulations can run in relevant commercial packages. Selection of the most appropriate approximation method is a decision of great importance as this will introduce or minimize the effect of extra uncertainties on the calculation. Available methods can vary from simple interpolation, using least square method analysis for polynomial regression, to more computationally intensive surrogate models that can capture extensive non-linearities and complexities of the response surface (Kolios and Casali, 2012). In the following sections both methods will be employed and compared accordingly.

Having characterized the stochastic variables and derived the response surface; various methods for probabilistic assessment can be employed. For a low expected probability of failure, Monte Carlo Simulations can provide efficient results however can become computationally expensive for values lower than $10^{-(4-5)}$. FORM/SORM can overcome the latter problem provided that surfaces under investigation do not provide extensive irregularities.

PROBABILISTIC ASSESSMENT METHODS

In this paper, two methods for surface approximation (response surface and kriging) and two for reliability analysis (MCS and FORM) will be employed and combined formulating methodologies with different efficiency. A final combination introduces a novel methodology that incorporates advantages of the above constituting an easy to numerically model procedure, referred to by the authors as “Dynamically Kriged Response Surface Method”.

Initially, after running the numerical simulations, output results are processed through polynomial regression and combined to MCS and then FORM. Subsequently, the output results are approximated through a surrogate modelling technique called kriging (Forrester et al., 2008) and then combined to MCS and FORM. Finally, a sequential combination that starts with a kriging approximation of the wider domain, followed by a polynomial approximation of the design point of each iteration of a FORM calculation loop, can form the newly proposed methodology by building quadratic polynomial surfaces close to the region of interest (eliminating the restrictions imposed by the surface shape). In the following section each of the methods will be applied (and validated) initially in the example of a single phase flow and later a two phase flow system.

CASE STUDY 1: VALIDATION THROUGH A SINGLE FLOW SYSTEM

Figure 2 presents a simple one-phase flow system that allows validation of the methods proposed and demonstrates their applicability. The system considered operates with water and has been modelled analytically through well-known fluid dynamics equations. The model has been validated using commercial software (PFE 2010) and hand calculations. The system pumps water from a tank into a straight pipe, which is joined to a back line, bringing back the fluid to the same tank. In particular the accuracy, ability to capture relatively low probabilities ($\sim 10^{-6}$) and required simulation time will be considered for the comparison. The main system dimensions/operating conditions are given in Table 1.

Table 1 System operating conditions and geometrical data

Elevation [m]	1	**Outlet pressure [Pa]**	101,325
Temperature [K]	293	**Pressure in A [Pa]**	233,960.3
Pipe length, total [m]	10	**Pressure in B [Pa]**	141,025.6
Diameter [cm]	5.2502	**Friction coefficient**	0.203
Pipe roughness [mm]	0.046	**Flow rate [m^3/s]**	0.01
Inlet pressure [Pa]	101,325		

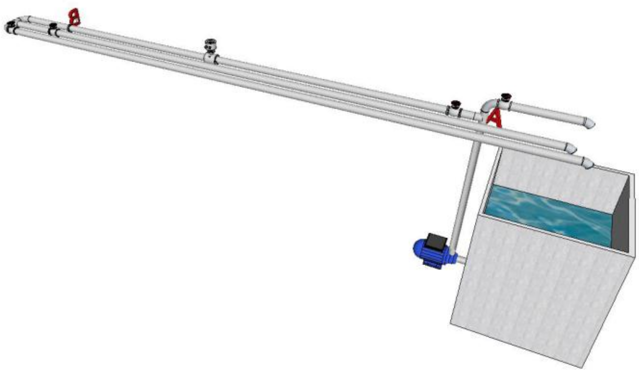

Fig.2 Reference system depiction

For this case four different scenarios exploring three failure modes were identified:

- maximum pressure allowable (in a pipe and in a flange-gasket-flange, point A and B respectively)
- minimum efficiency allowable for the pump
- minimum pressure difference for pressure-driven flow

All limits are assumed and not related to actual system known limits. Limits for scenarios 1A and 1B are set to 280,000 Pa and 200,000 Pa respectively, limit for pump efficiency is set to 61% for scenario 2 and the one for scenario 3 is set to the condition of having more than atmospheric pressure at the outlet point.

The variables affecting the operative performance are identified and their uncertainty is represented by CoV and listed in Table 2. Not all of the identified parameters are used in all the scenarios: in particular for scenarios 1 and 2 the first six are considered and for the last one all of them are considered.

Table 2 Stochastic Variables

	CoV	**Reference**
Pressure	0.50%	(Elster, 2013)
Temperature	0.20%	(Elster, 2013)
Flow rate	0.50%	(Elster, 2013)
Roughness	10.9%	(Wyant and Creath, 1990)
Level	0.5%	(Fulford et al., 2006)
Pump characteristic	10.1%	(ISO 9906:2012)
Valve pressure drop	1.54%	(Sandalci et al., 2010)

Figure 3 and 4 show the results from the techniques employed and developed. As it can be shown, simple SRSM-FORM can estimate well the reliability index in some of the scenarios but not for 1B where the probability of failure is largely under-estimated. Focusing on this and trying to understand if the low accuracy is introduced by SRSM or by FORM; further analyses have been carried out excluding those two techniques once at a time. Using SRSM-MCS results are still insufficient but better than previously, implying that inaccuracy is due to SRSM. Performing analysis using kriging and MCS this trend can be confirmed. Removing both SRSM and MCS from the analyses combining kriging and FORM using the innovative and previously illustrated techniques the results match the ones obtained through direct MCS.

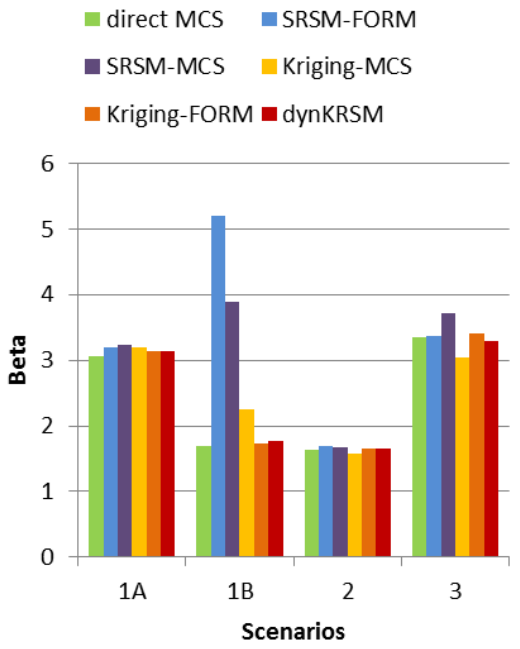

Fig.3 Safety index results

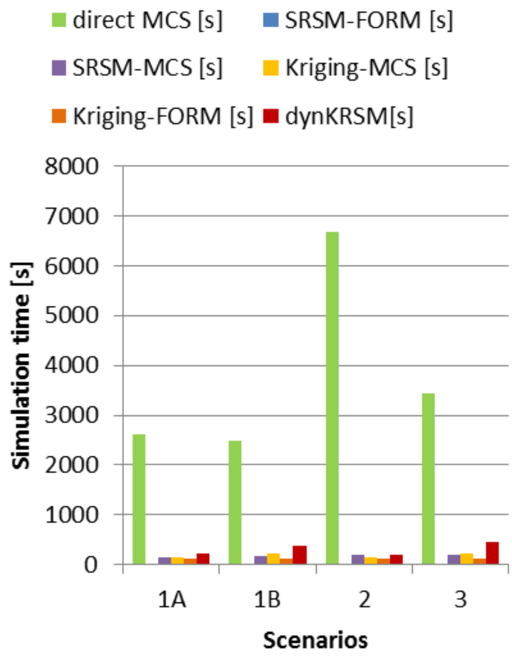

Fig.4 Computation time (sec)

It can further be concluded that Dyn-KRSM and kriging-FORM methods present a simulation time comparable to the surrogate MCS and largely lower than direct simulation. Analysing scenario 1A only and formulating the LS in order to explore more extreme situations (limit pressure moved up to 327,000 Pa) it is possible to test the ability to accurately calculate lower probabilities of failure of the newly developed methodologies. Benchmarking was done using MCS up to 10^7 runs.

CASE STUDY 2: TIME-DEPENDENT RELIABILITY DETERIORATION OF A TWO PHASE FLOW SYSTEM

This more complicated example considers a two-phase flow system, in particular a pipeline and a riser heading from the wellhead to the top riser (e.g. platform deck). The system is assumed to partly lie on the sea floor transporting oil and natural gas. The platform is standing 510 m from the seabed and 30 m above the sea water level. The well is located 255 m below the sea surface. The riser is vertical and 510 m long, followed by a 100 m horizontal top-side pipe. Both have a 4 inch (0.1 m) diameter pipe having 0.0075 m wall thickness. The pipeline connecting the well head to the riser base is composed of 4 pipes laying on the sea bed which is irregular and going deep up to 500m. This pipe is 0.12 m diameter and has 0.009 m wall thickness. All the pipes are assumed to be made from steel. The sea water temperature is assumed to be 6° C, the well pressure 100 bar, the mass flow rate 15 kg/s and the heat transfer coefficient 6.5 W/m2°C.

The two-phase system analysed is modelled in specialised software for offshore pipeline applications, OLGA © from SPT Group. Here just steady state simulation will run since slug control and detection goes beyond the actual scope of the work. The software is able to provide values of pressure and temperature section-wise, where section length is given in the modelling stage. Here it is chosen around 100 m. The benefit of employing a non-intrusive methodology approximating the response of a system with appropriate methods, allows the use of such dedicated tools without requirement for extensive modelling in a unified assessment procedure. Internal corrosion is assumed to be affected by CO_2 content only. This is reasonable because of the absence of water/sand in the pipe and assumed external protective coating on the pipeline. Therefore, corrosion rate is modelled based on well-known DeWaard and Milliams correlation (Bai et al., 1994) and (Alfon et al., 2011).

The uncertainty levels considered for this particular case expressed in terms of CoVs are listed in Table 3 below with relevant references. The maximum pressure permitted in a pipe, so that the pipe itself withstands the load, is given by Barlow's formula; this is mainly depending on yield strength, thickness and diameter. The last one can be considered as deterministic due to low variation during service life, but the first two have to be considered stochastic. Thus stochasticity is introduced also in the limit state that can be formulated in terms of MOS as the limit value minus the actual value. A surrogate model is then built directly from stochastic inputs (stochasticity coming both from system inputs and system limit) to the MOS values. Regarding internal corrosion, thickness deterioration occurs over time so that the pressure that the pipe can withstand is diminished. The safe operability level, represented by the safety index, is also changing overtime and in particular decreasing. An estimate of the time needed before inspection or maintenance can in this way be done choosing some target safety levels (Bai, 2001). In this application limits at 10^{-4} and 10^{-5} are chosen as maximum danger and warning levels (Ultimate Limit State and Serviceability Limit State).

Table 3 Stochastic Variables

	CoV	**Reference**
Well pressure [bar]	1.00%	assumed
Temperature [°C]	0.20%	assumed
Multiphase Flow rate [kg/s]	0.30%	(Norwegian society for Oil and Gas Measurement, 2005)
Pipe roughness [mm]	10.70%	(Wyant and Creath, 1990)
Sea temperature [°C]	0.80%	(ESA AATSR, 2012)
Heat transfer coefficient [W/m^2.°C]	10.00%	assumed
Yield strength [MPa]	1.00%	(Kolios and Brennan, 2012)

Visualizing the results of reliability assessment in each of the segments of the pipeline, Figure 5 illustrates the failed segments after 2.7 years of operation, under effect of corrosion, also taking into account the relative target safety levels as prescribed by standards. Figure 6 shows the relevant deterioration of reliability through time. As it can be observed, performing discrete events analysis over time can provide a trend of the safety index and give an estimate of the system safety at intermediate time (interpolating properly discrete results obtained). Once target reliability levels are defined for the system under study, the expected time of crossing these levels can be estimated, so as to plan just local inspection and maintenance tasks in the most critical segments.

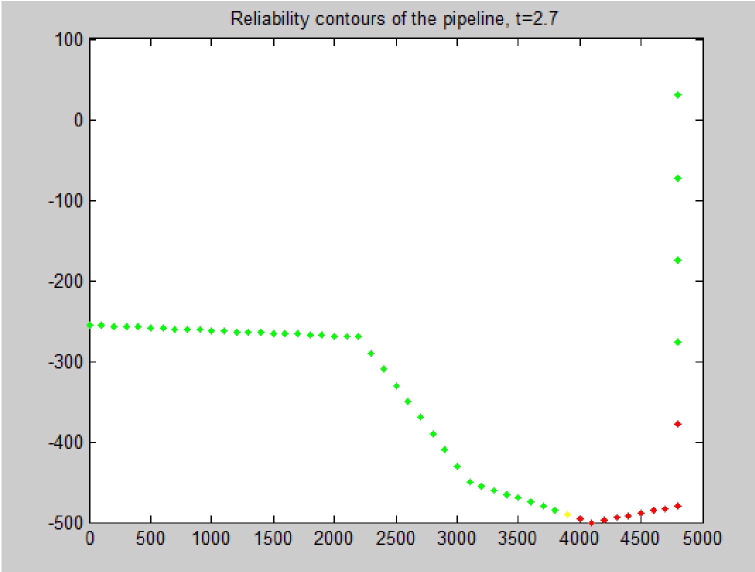

Fig.5 Safety Levels exceedance map for t=2.7 years

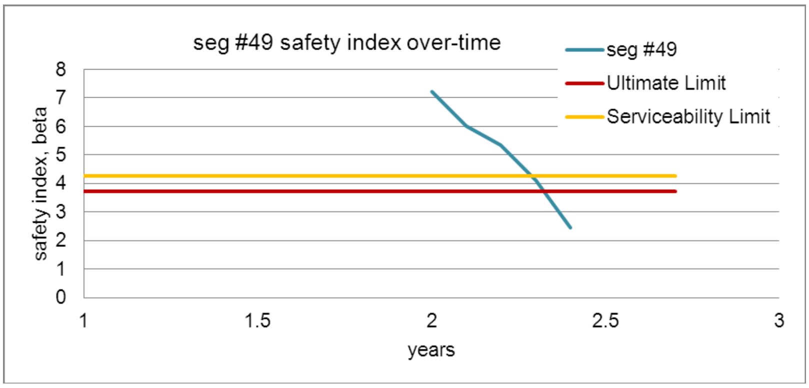

Fig.6 Safety index over time for critical segment of pipe

Comparing the methods employed, Dynamic kriging is shown to be working efficiently for this example. Kriging-MCS results appear just from a certain point in time on, when P_f is high enough to be estimated by MCS (Table 4).

Table 4 Safety index estimation methods comparison

year	SRSM/FORM	dyn kriging	kriging/MCS
1	-	-	-
1.5	-	-	-
2	-	8.16	-
2.5	6.69	6.24	6.12
3	4.79	5.17	443
3.5	1.84	0.78	1.29

CONCLUSIONS

In this paper a quantitative reliability assessment of two cases of flow systems are presented following different methodologies and comparing results. Conventional reliability analysis tools have been transferred successfully from structural design applications where they have been extensively applied. In this work the development of a novel method is also documented, combining conventional kriging with stochastic response surface method and analytical methods for reliability assessment (i.e. FORM). Among the methods applied and benchmarked, the new proposed one - referred to as "Dynamically Kriged Response Surface" method - is found to provide very efficient results combining higher accuracy with reduced computational time.

Further applications to even more complicated systems might further highlight the potentials of the proposed methodology in terms of both increased accuracy and ability to capture very small probabilities of failure that cannot be conveniently estimated by direct simulation methods.

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