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Performance analysis for subsea blind shear ram preventers subject to testing strategies

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ABSTRACT

In a subsea blowout preventer system, a subsea blind shear ram preventer (BSRP) plays as a crucial safety barrier by cutting off the drill pipe and sealing the wellhead to prevent serious accidents. Testing and repairs of BSRPs are the main issues in operation and maintenance activities. It is important to assess BSRPs unavailability during proof and partial testing phases in order to ensure their safety functions. This paper presents a newly state-based approach for unavailability analysis by incorporating testing activities of BSRPs into multiphase Markov process. In the approach, states waiting for repair are taken into consideration. Analytical formulas for evaluation of time-dependent unavailability and average unavailability for BSRPs are developed. In addition, the non-periodic characteristics and effects of degradation are also taken into account in proof testing. The effects of testing errors and postponed repairs on the tendency of unavailability in partial testing phases are checked in the proposed models. Performance analyses for BSRPs configurations, scenarios and cases considered in the paper are carried out to demonstrate the application of the proposed models. Monte Carlo models for both proof and partial testing are developed and simulated. Different comparisons are performed for validation of the set of the derived formulations.

1. Introduction

Blowout, a phenomenon that the uncontrolled formation fluid (crude oil and/or natural gas) may release into the external environment, primarily occurs in the exploitation of oil and gas fields after pressure control systems have failed. Subsea blowout preventer (BOP) is an effective offshore well control system used to prevent blowouts by closing and sealing the well bores [1]. Blind shear ram preventer (BSRP) is the crucial last layer of defense in a BOP system when the pressure within the drilling system becomes uncontrollable. If the BSRP is available on demand, a blowout will not occur. The reliability and availability of BSRP is always very important. However, it is reported that a BSRP may fail in chance of 50% when attempting to shear pipe during actual operations [2]. The well-known “Deepwater Horizon explosion” accident in Macondo drilling rig on April 20, 2010 [3] is caused by the failure of the subsea BOPs and BSRP in particular, as one of main reasons, finally resulting in the catastrophic consequences.

A BSRP in subsea environment may suffer from the failures. Some studies have investigated the failures of BRSPs, e.g. Han et al. [4] have studied the damage and failure of the shear ram of the blowout preventer in the shearing process by a numerical simulation and an experimental investigation. Klingsheim [5] has given about qualitative analysis of subsea BSRPs including failure modes. The recognized industry regulations and stands requirements have been made to reduce the unavailability. BOPs must be tested and testing strategies are implemented to discover the possible failures [6–8].

Generally, existing methodologies used for BOP reliability analysis can be categorized into two types: static methods (including fault tree analysis (FTA), failure modes and effects analysis (FMEA) and Bayesian network (BN)) [9–11], and dynamic methods (Dynamic BN (DBN), Markov model, and Petri net etc.) [12–14]. FTA and FMEA are widely used in detailed BOP reliabilities studies according to the reports by Holand et al. [15–17]. BN methods have been used by Cai et al. [18] to assess the reliability of subsea BOP control systems, including triple modular redundancy and double dual modular redundancy control systems. Common cause failures and imperfect coverage are taken into account as two important features. However, these approaches that are applied in a static situation are unable to capture dynamic effects during operation processes. On the side of dynamic methods, Cai et al. [19] have presented a novel real-time reliability evaluation methodology based on BNs and DBNs for a subsea pipe ram BOP system, and the same authors also consider imperfect repair and preventive maintenance

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in performance evaluation of subsea BOPs and control systems [20,21]. Liu et al. [22] have developed deterministic and stochastic Petri nets models to evaluate the performance of subsea BOP system. Effects of failure rate and repair time of each component on system steady-state availability have been analyzed. Kim et al. [23] have performed availability analysis of BOP by building Markov models where the demand rates are considered. Common causes failure is described by the updated β factor model that is capable of overcoming the problem of the same β factor and distinguishing different voting logics. The above-mentioned methods have focused on reliability analysis for a BOP system. However, assessments of BSRPs in real world may consider many complex situations such as flexible duration of testing, the real degradation of components, testing errors and different maintenance strategies.

Multiphase, multiphase Markov or phased mission system analysis is referred as another dynamic reliability analysis method which has been developed by some research works [24–26,44]. These methods have been applied to safety instrumented system for reliability assessment. For instance, Innal et al. [13] have established new generalized formulations with repair time using the multi-phase Markov models. Mechri et al. [27] have used the fuzzy multiphase Markov chains to assess the performance of safety instrumented systems (SISs) in low demand mode. Expert judgment is adapted to evaluate the impact of uncertainty. Langeron et al. [28] have presented multiphase Markov approach to formalize the probability of each state of a SIS, and also have investigated the robustness of IEC61508 merging rules in an analytical way. A BOP test from one phase to another is also a multiphase process. A multiphase Markov model has been presented by Strand and Lundteigen [29] for BOP system reliability assessment during well drilling phases for risk control, and this model can be used to support decision-making about maintenance policies.

Several issues, however, need to be further investigated when they are applied to the subsea BRSPs:

- The dynamic behaviors involving testing characteristics (errors may exist during the testing) and maintenance effects on unavailability are ignored.
- Only periodical proof test is considered in Markov models. In addition, failure rates are always assumed to be identical in every phase, meaning that deterioration is not in consideration.
- Challenges from subsea context are not well handled with, for instance, the non-ignorable time to repair even for a revealed failure. Repairs for subsea facilities are always postponed since: Firstly it is difficult to access to subsea equipment, and secondly, some potential well blowout risk may increase due to the unscheduled pulling of a BOP for repair.

In order to overcome these limitations, this paper proposes a new approach based on multiphase Markov process for developing unavailability analytical formulas that consider maintenance characteristics during testing phases. The main benefit of the proposed approach is a more efficient and realistic process, where the potential factors and the effects of maintenance strategies are taken into account compared with the typical BOP reliability analysis [18]. In addition, regarding other dynamic models such as simple Markov process or Petri-nets, the benefits are specified as follows:

- Compared to simple Markov process, multiphase ones allow to take into account periodic or deterministic time for inspection, and changes of the failure rate between different phases.
- Compared to Petri-nets simulation, multiphase Markov process can give an exact close formula for the unavailability assessment in modeling testing errors.

The potential contributions can be specified as:

- Maintenance durations for BSRPs in different phases are involved. Dynamic behaviors of a system during repairs are considered in unavailability analysis.
- Degradation is taken into account during proof testing. The increasing failure rate in different phases is also modeled in the calculation of unavailability for dynamic predication.
- Testing characteristics are also taken into consideration, including testing errors in partial testing phases, non-periodic testing, and detection delay.

The reminder of the paper is organized as follows. Section 2 describes in detail the subsea BOP system and the subsea BSRPs, their operation and failure modes, as well as the testing and repair activities. Section 3 illustrates the proposed approach for building multiphase Markov models and developing the approximation formulas for unavailability analysis given the certain assumptions. Section 4 presents the corresponding numerical results for performance analysis in consideration of the non-periodic characteristics and effects of degradation during proof testing phases, and the testing errors and repair time during partial testing phases. Section 5 has compared the numerical results from the approximations with those from the Monte Carlo simulation to validate the proposed approach. Concluding remarks and suggestions to future works are given in Section 6.

2. System description

2.1. Subsea BOP system

The subsea BOP system mainly consists of subsea BOP control system and subsea BOP stack. The subsea control system is comprised of electrical system and hydraulic system such as pumps, valves, accumulators, fluid storage and mixing equipment, manifold, and other equipment [22], which is out of the scope of this paper. A typical subsea BOP stack is illustrated in Fig. 1. The subsea BOP stack is usually equipped with Lower Marine Riser Package (LMRP) connector and wellhead connector which are activated hydraulically and used to connect the LMRP to the BOP stack or the BOP stack to the wellhead in the seafloor. It also mainly includes annular preventers, ram (pipe ram, shear ram) preventers, and other components, for instance, the flexible joint and choke valves and lines [18]. Annular preventers are hydraulically operated to seal off different sizes of annulus whether drill pipe is in the wellbore or not. However, annular preventers are generally not as effective as ram preventers in maintaining a seal on an open hole [30]. Ram preventers are similar to a gate valve in operation to some extent and used to close and seal the hole when they are activated. Pipe ram preventers close around a drill pipe, and shear ram preventers must cut off the drill string or casing with hardened steel shears for emergence situations e.g., kicks or potential blowouts. BSRPs, which are the last line of defenses against blowout, are intended to cut off the drill pipe if present and effectively seal the hole against release of oil/gas/drilling mud.

2.2. Configurations

According to the configurations of ram preventers and minimum redundancies requirements, BOP stacks can be classified into a conventional BOP stack and a modern BOP stack, respectively. As shown in Fig. 1(a) and (b), a modern subsea BOP typically has two annular preventers, four pipe ram preventers and two blind shear ram preventers, while a conventional subsea BOP has two annular preventers, three pipe ram preventers and a blind shear ram preventer. Fig. 1(c) indicates the simplified BOP configurations and components number. Compared with the conventional configuration, BSRPs in the modern BOP configuration are parallel subsystems with two components and pipe ram BOP subsystem is a parallel subsystem with four components. The different configurations of preventers lead to different performances for subsea BOP system. Such redundancies aim to give functional availability in case of system or subsystem failures during blowout occurrence. Therefore, BSRPs as a critical subsystem of the BOP stack may be modeled with basic 1oo1 or 1oo2 configurations [23,30,31] for performance analysis in this research.