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Applied research of Primary Pump Mission Profile construction

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ABSTRACT

The traditional Mission Profile analysis did not clarify the accurate concept of minimum subtask and component. However, there are several components, which could be the influencing key element of the system reliability; and there are several subtasks, which could be used as a basic and crucial mission. In this paper, traditional method of Mission Profile has been extended by incorporating two new ideas: Minimum Associated Subtask (MAS) and Minimum Effective Component (MEC). This method of Mission Profile modeling is derived from Chinese 1000 MW NPP Primary Pump localization. A case study on Primary Pump reliability has been presented; then, MAS and MEC have been existed as vital elements in its lifecycle profile construction. By means of MAS and MEC, Mission Profile plays a more important role on complex system (Primary Pump) reliability analysis.

1. Introduction

China is conducting world's largest self-reliance nuclear power plant (NPP) construction plan. Localization practice focus on aligning national interests with scientific goals, localization design and manufacturing capabilities.

Primary Pump is a vital nuclear class component. Reliability of its operation directly affects operating economy and safety of NPP. To be specific, pump performance needs to meet design requirements without sacrificing operation reliability. It would be ideal that economical considerations are incorporated into predetermined design criteria for certain mission critical components. It is a significant task that evaluation of reliability of Primary Pump in ongoing Chinese million kilowatts (i.e. 100× MW) class shaft seal coolant pump localization research and development (R&D).

In NPP, traditional electrical system reliability is evaluated by classical Probabilistic Safety Assessment treatment based on the components failure probability and generic data (Nayak et al., 2009; IAEA, 1988). In practice, due to the lack of availability of sufficient failure data, multiple options of reliability assessment relying on adequate data are difficult to perform (Nayak and et al., 2009; Department of Defense, 1991; Hari Pasad, 2011). Primary Pump is complex electromechanical system without sufficient failure data accumulated and environment changing. Hence, Failure Mode could be used for quantitative analysis of complex system reliability which is widely used in nuclear industry (Ramakrishnan, 2016). Meanwhile, identification of the system Failure Mode is important step for complex system reliability analysis (Zio et al., 2010). The authors use Mission Profile to indicate whether the target equipment can perform its function throughout designed full life cycle or just mission time. Mission Profile can also reveal the environmental conditions. The Mission Profile model approach, as a desirable feature of the prognostic methodology to identify the system Failure Mode, is based on the basic reliability principle providing details of all factors previous affecting reliability. And, that is the fundamental of the further electromechanical system reliability modeling.

Profile analysis is a systematic (system level) analysis which is part of top-level analysis includes two procedures: Life Profile and Mission Profile.

Before further investigation, we introduce definition of Mission Profile: a time-phased description of the events and environments an item experiences from initiation to completion of a specified mission, to include the criteria of mission success or critical failures (MIL-STD-721C, 1981). When describing Mission Profile, general description of the product should work within the sequence, job content, duration, etc. to complete the task definition. And, when the product is a complex mechanical system, all tasks need to be the time sequence of the process described: the precise definition of the task and complete the standard, to determine the case of products into the major subsystems and components in which the working status and the stage, clarify the time sequence and duration of class work state, to determine the environmental properties and various environmental conditions, time sequence

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and duration (Lakner and Anderson, 1985; Whitten and Dentley, 2007).

Life Profile of a particular product could contain more than one Mission Profile. Knowledge of different parts (components) performance during subtasks throughout entire system lifecycle under working conditions (including environmental conditions) is required for complex system reliability analysis. Information provided by above process is an essential input for performing following Failure Mode and Effects Analysis (FMEA) and reliability modeling construction.

Here, product reliability (R_i) could be generally expressed as a function of time (t), condition (c), and functions (F) Lakner and Anderson, 1985; Whitten and Dentley, 2007:

$$R_i = f(t, c, F). \tag{1}$$

For a complex system which is composed of several subsystems, R_i is derived from an internal dynamic composition relationship between the system and its all subsystems. Dynamic composition could be interpreted as description of composition changes brought by configuration changes. Hence, system reliability (R_s) depends on component reliability and different composition (which is formalization as $C(t)$ Lakner and Anderson, 1985; Whitten and Dentley, 2007):

$$R_s = f[R_i, C(t)]. \tag{2}$$

Several monographs (MIL-STD-721C, 1981; Lakner and Anderson, 1985; Whitten and Dentley, 2007) describe the applications of definitions of reliability, profile, FMEA in complex systems analysis. Hence, due to combine all the parameters above, ‘‘the reliability of the product" is finally determined via a Mission Profile construction. Mission Profile analysis is a method widely used in complex system reliability, as well, such as photovoltaic system (de Leon et al., 2016), aeronautic system (Charruau et al., 2006), when failure data is not available.

In this paper, the authors choose the ‘‘shaft seal pump" as a ‘‘product". The shaft seal pump (Primary Pump) has variety functions and complete variety of tasks. In order to carry out the investigation of Failure Mode and the subsequent reliability modeling, it's needed to focus on the minimum function (task) within each of the cross-sectional views of a cross-sectional contribute and the minimum investment unit. In terms of the engineering practice and through the feedback from each links of reliability engineering actions in Primary Pump R&D program, we find the bottleneck of Mission Profile analysis is identifying subtasks and categorizing/recognizing components under different environment (stress) conditions. In this study, Minimum Effective Component (MEC) and Minimum Associated Subtask (MAS) were introduced, and used to conduct profile analysis. Corresponding internal logic described above is shown in Fig. 1. We propose these two terms to describe real engineering practice in Mission Profile construction of Chinese 1000 MW NPP Primary Pump.

2. Mission Profile analysis method

Profile analysis is based on the mechanistic modeling approach providing details about the various failure mechanisms. It is improved that the understanding of the root causes and driving forces of failures. A series of failure mechanisms are involved with the model approach, such as crack growth, corrosion, creep, fatigue and impact (Hari Prasad, 2011), which are foundations for further reliability analysis. Traditional Mission Profile analysis takes mission time, environment condition into consideration and does not clarify the accurate concept of minimum subtask and component. When systems increase internal complexity with more components involved under multiple tasks, key elements reliability could have more significant impact towards mission critical situations.

2.1. Introduction of the product

To achieve major Generation III NPP functions of primary coolant pump, the product in the current research adopts advanced modular design and manufacturing techniques (Naval Surface Warfare Center Carderock Division, 2011).

The pump consists of the pump body module, motor module, auxiliary system module and control module. Each module contains multiple submodules. And each module has its own task responsibilities. So, Fig. 2 completely reflects the structure and the corresponding function of the Primary Pump in this research (Naval Surface Warfare Center Carderock Division, 2011; Zang and Shen, 2007).

In practice, it is required to take consideration both of system level equipment composition and task level product functions. After the analysis scope is determined, ‘‘Primary Pump (Completed Machine) – main module – sub-module – (mechanical) components or parts", top-down analysis could be used. Generally, four types of profiles need to be constructed: (1) one Primary Pump (overall) Mission Profile; (2) four Mission Profiles of each main module; (3) several Mission Profiles of each sub-module; (4) several profiles of major components.

Meanwhile, when R&D engineers focus on the functions of the Primary Pump is completed machine, it is necessary to determine: i) Driving Coolant Flow and ii) Pressure Boundary Integrity, for system level Primary Pump mission description.

Four descriptions may be necessary when performing extensive task hierarchical logical analysis: (1) major events and other possible basic events under each individual mission stage; (2) time sequence, ergodic process (i.e. the orders); (3) each mission phase task success criteria; (4) environmental condition.

2.2. MEC and MAS

In the current research, traditional method of Mission Profile method has been extended by incorporating two new ideas of MAS and MEC. Minimum Effective Component (MEC) is defined as: when product carries out a related mission, minimum components or the sub-modules in this product, which can affect to exert influence on the reliability of the complete machine. Here, establishing Mission Profiles to this kind of component has some engineering significance. Thus, MEC has the following two properties: (1) In specific Mission Profile of complete machine, the MEC is the smallest unit that contributes to overall equipment reliability. (2) Clarity, when performing MEC analysis, each module running state is deterministic, component state change in each phase affects overall reliability which could (also) be observed through model change.

In particular, taking development of Primary Pump as an example, under MEC definition, components can be divided into four categories (not exclusive of each other): (1) standard components or common non-standard components don't undertake independent task; (2) simple-structure components need to cooperate with other components to complete certain functionality; (3) running condition/environment doesn't change or under normal environment stress; (4) geometric shape time invariant components and other properties time invariant components. The parts have four features above, are not MEC, do not need their own Mission Profile.

From system reliability perspective, in single Mission Profile, basic reliability of the system is: