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Reliability assessment of complex electromechanical systems under epistemic uncertainty

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ABSTRACT

The appearance of macro-engineering and mega-project have led to the increasing complexity of modern electromechanical systems (EMSs). The complexity of the system structure and failure mechanism makes it more difficult for reliability assessment of these systems. Uncertainty, dynamic and nonlinearity characteristics always exist in engineering systems due to the complexity introduced by the changing environments, lack of data and random interference. This paper presents a comprehensive study on the reliability assessment of complex systems. In view of the dynamic characteristics within the system, it makes use of the advantages of the dynamic fault tree (DFT) for characterizing system behaviors. The lifetime of system units can be expressed as bounded closed intervals by incorporating field failures, test data and design expertize. Then the coefficient of variation (COV) method is employed to estimate the parameters of life distributions. An extended probability-box (P-Box) is proposed to convey the present of epistemic uncertainty induced by the incomplete information about the data. By mapping the DFT into an equivalent Bayesian network (BN), relevant reliability parameters and indexes have been calculated. Furthermore, the Monte Carlo (MC) simulation method is utilized to compute the DFT model with consideration of system replacement policy. The results show that this integrated approach is more flexible and effective for assessing the reliability of complex dynamic systems.

1. Introduction

The large complex electromechanical systems (EMSs) have been widely used in aviation and aerospace industry, electric power system, civil machinery, etc. The complexity of system structure and formidable manufacturing cost has limited the system level reliability tests of those EMSs. It also makes the system reliability indexes evaluation become infeasible, since a long time reliability test and large quantities of statistical data are needed. In practice, only a small amount of experimental data, field data and engineering experience information are available, which makes it almost impossible to evaluate the lifetime and reliability of system through data analysis. Furthermore, the uncertainties caused by the lack of data or knowledge, and the dynamic behavior also affect the reliability of the EMS. Therefore, there is a strong requirement to take a series of technological means to evaluate the reliability indexes of EMS, and a comprehensive reliability assessment of the entire system must be performed. Furthermore, the consideration of dynamic uncertainty and maintainability of system or components is a crucial issue to be resolved for the assessment of the reliability of complex EMS.

Reliability assessment [1–3] is implemented through the design, testing, production, storage and usage phases of a product or system, it is a process of analyzing and confirming the reliability of system and its components. It is also a qualitative and quantitative analysis technique to model and predict system reliability throughout the product lifecycle. There are basically four aspects of technical contents of system reliability assessment, including reliability modeling, reliability data collection and processing, unit reliability assessment and system reliability synthesis.

To obtain the reliability of a complex EMS, the reliability model should be built to describe the failure logic relationship between the whole system and its compositions. In recent decades, various reliability modeling methods have been developed for complex systems and the accuracy of the models is improved. Some classical static modeling techniques, including reliability block diagram model, fault tree (FT) model, and binary decision diagrams (BDD) model, have been widely used to model static systems. While considering the complexity of modern EMSs, the dynamic modeling techniques such as Markov model [4], dynamic fault tree (DFT) model [5], and Petri net model [6] have been applied for reliability modeling. DFT analysis method, first proposed by Dugan

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et al. [7,8], is a mature and important method in reliability analysis of dynamic systems. Since then many variations have been published. As such, three criterions are given to rank basic events of DFT, and a transforming method of logic gate is put forward by Hao et al. in [9]. Approximate DFT calculations are presented by Lindhe et al. [10] based on a Markovian approach, which was used for water supply risk modeling and performed by standard Monte Carlo (MC) simulations. Considering the interactive repeated events in different dynamic gates, Merle et al. [11] proposed a new analytic method to solve DFTs with priority dynamic gate and repeated event. An improved sequential BDD method was proposed for quantitative analysis of DFT with interactive repeated events by Ge et al. [12]. Considering the state explosion and computational efficiency problems in DFT model, Mo [13] proposed a multi-value, decision-diagram-based DFT analysis method to analyze the reliability of large dynamic system. A MC-based approach was investigated by Rao et al. [14] to solve dynamic gates, which can be used to alleviate the state space explosion problem. To overcome the limitations caused by the increasing size of FTs in traditional reliability assessment, Chiacchio et al. [15] proposed a Weibull-based composition approach for large DFT to reduce the computational effort. In view of the dynamic characteristic in modern complex EMS, and taking advantage of the dynamic modeling ability of DFT, a DFT model should be built on the basis of system structure and failure behaviors.

As an inheritor of FT, Bayesian network (BN) has a similar state description and reasoning pattern with FT method. It also has the advantage of dealing with multi-state modeling and non-deterministic fault logic representation [16]. BN is a directed acyclic graph (DAG) for system modeling, which is a mathematical model based on probability reasoning [17]. It was first proposed by Pearl [18,19] and has been widely used in reliability and safety analysis. Cai et al. [20] proposed a BN-based approach for reliability evaluation of redundant systems including parallel systems and voting systems by taking account of common cause failures and imperfect coverage. Khakzad et al. [21] presented a new formalism to model cold spare (CSP) gates and sequential enforcing gates with various types of probability distribution functions. Under this formalism, the discrete-time BNs were applied in risk assessment and safety analysis of complex process systems. In [22], BN was used to solve the Pandora temporal FTs, which is a dynamic analysis technique that can capture the sequence-dependent dynamic behavior of system. To overcome the shortcomings of traditional fault tree analysis method, a systemic decision approach was presented in [23] by integrating the predictive, sensitivity and diagnostic analysis techniques in DBN inference. BN has been used for reliability analysis of complex systems with various kinds of uncertainties, and it has an advantage to facilitate the estimation of system reliability by coping with system complexity. Su and Fu [24] presented a causal logic method for qualitative modeling of the BN reliability model of wind turbine when considering the environmental factors and uncertainty.

Except for the nonlinear dynamic characteristic, the uncertainty existing in complex EMS is always another important issue which cannot be ignored. There are basically two types of uncertainties, aleatory uncertainty and epistemic uncertainty. Aleatory uncertainty arises from intrinsic variability and is irreducible, which is also called objective uncertainty. It can be described and propagated by probability theory. Epistemic uncertainty results from incompleteness of knowledge or lack of data, it is called subjective uncertainty [25,26]. Alternative theories and methods have been proposed to represent epistemic uncertainty, such as interval theory [27], evidence theory [28,29], possibility theory [30], info-gap theory [31], random sets [32], fuzzy sets [33], Bayesian approaches [34], probability-box (P-Box) [35–42], etc. P-Box has an advantage for tackling the uncertain parameters without precise probabilistic models in view of epistemic uncertainties. A P-Box is specified by lower and upper (interval-type) bounds on the cumulative distribution functions (CDFs) of uncertain variables [35]. It has been widely used in reliability and risk analysis and is suitable for diverse engineering fields. To build the connection of P-Box with other uncertainty representations, a generalized form of P-Boxes was defined by Destercke et al. [36]. Bayesian P-Boxes are used by Montgomery [37] for risk assessment with multiple parameters distributions. Zhang et al. [38] proposed an interval MC method. An interval importance sampling method [39] and an interval quasi-MC simulation method [40] in structure reliability analysis with the parameter uncertainties modeled by P-Boxes have been investigated also. P-Box was applied as a visual tool by Mehl [41] for cost uncertainty analysis. Furthermore, Yang et al. [42] studied the hybrid reliability analysis under both aleatory and epistemic uncertainty cohere random variables and P-Box variables. To reduce the impact of uncertainties on systems, the representation and quantification of uncertainty need to be addressed first. For the epistemic uncertainty induced by incomplete data, based on the definition of P-Box, an extended parametric P-Box to is proposed to represent the uncertainty in complex EMSs.

Moreover, the maintainability or reparability of components can improve the reliability of whole system. When the replacement policies are considered in EMSs with repairable components, the MC simulation method can be used to compute the reliability model. MC simulation method is a widely used method in reliability analysis of complex systems. By using MC simulation method, the system reliability can be calculated and the effect of a variety of related factors (system reparability, dependency, etc.) to system reliability can also be evaluated. In this regard, Taheriyoun and Moradinejad [43] have combined the FT analysis method with MC simulation method for reliability analysis of waste water treatment plant. Manno et al. [44] presented a MC-based high level modeling framework that is integrated with FT method for reliability assessment of complex system with time dependencies. They also gave a definition of repairable DFT in [45], and a Matlab toolbox named RAATSS was presented based on adaptive transitions system formalism. This can be used to model and evaluate occurrence probability of top event when both repairable and non-repairable subsystems are considered. On the basis of structure function of DFTs, Merle et al. [46] proposed a quantitative analysis method based on MC simulation. The structure function was exploited, and the minimal cut sequences (MCSQs) can also be determined by this MC-based method. A MC DFT method was proposed by Zhang et al. [47] to analyze the reliability indexes of phasor measurement unit.

When considering the dynamic characteristics, uncertainty and maintainability of a system or components, a comprehensive reliability assessment process of complex EMSs has been proposed in this paper. The rest of this paper is organized as follows. In Section 2, a BN reliability modeling process is introduced based on DFT model, and the lifetime of dynamic logic gates is defined. The lifetime distribution analysis has been performed based on the coefficient of variation (COV) method. Section 3 constructs a MC simulation-based framework for lifetime and reliability assessment of complex EMSs with consideration of system reparability. An extended parametric P-Box is defined to present the epistemic uncertainty in Section 4. A case study of an EMS has been presented to demonstrate the effectiveness of the suggested reliability assessment framework in Section 5. Finally, conclusions are made in Section 6.