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Research paper

Time-dependent reliability based design for control of servo linkages with unknown but bounded uncertainties

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ABSTRACT

Due to the inevitable phenomena that various uncertainty factors in the servo mechanisms severely affect the output motion accuracy and the exact statistic characteristics of uncertainties may extremely difficult to be gained since the lack of sample information in practice, the non-probabilistic dynamic reliability assessment and optimization with high confidence and efficiency is of great significance for scientists and engineers. In view of this, this study develops a novel approach of non-probabilistic reliability based controller design for servo mechanisms and the related solution details are further expounded. The uncertainty quantification of dynamic response is conducted by the combination of the first-order Taylor expansion and interval mathematics. The non-probabilistic reliability with consideration of time-dependency for servo mechanisms is obtained by the first passage theory and interval process model. By comparing with the Monte–Carlo simulations (MCS) and the robust design approach, the accuracy of proposed reliability index and the applicability of the developed reliability based controller design method are demonstrated in two numerical examples.

1. Introduction

A mechanism is a mechanical device which can transfer the input motion/force into a desired output motion [1]. Due to the significant development of the modern control technology, the servo motor is widely used as power source of mechanisms which can ensure the mechanisms perform its tasks precisely [2]. Actually, the mechanism powered by servo moto, namely, servo mechanism is an organic combination of the sensors to measure the response, the actuators to give the power and the control law to analyze, maintain and correct the output performance based on feedback signals [3].

The concept of design for control (DFC) is formally presented by Li et al., and the ultimate aim of DFC is to pursue the best control performance by optimizing the parameters of controller [4]. Many researchers made a lot of contribution to introducing the DFC approaches into the servo mechanism design problems. Aiming at solving the design problems of programmable closed-loop mechanism, Zhang et al. presented a new design approach by integrating the structural design and DFC [5,6]. Wu et al. proposed the optimization method for the PD controller of the high-speed closed-loop mechanisms [7]. Yan et al. conducted the integrated optimization for the variable input-speed servo four-bar linkages powered by PID controller [2]. Roos et al. developed a DFC approach for the servo systems [8]. Al-Hamouz et al. conducted the optimization for a DC motor by genetic algorithms [9]. Reyer et al. developed a new integrated design for the DC Motor by the combination of dimension design and controller design [10].

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In practice engineering, the uncertain factors in servo mechanisms are notable, impersonal and ubiquitous because of the environment changes, operating conditions, manufacturing variations and signal errors [11,12]. However, by virtue of deterministic assumption, the aforementioned studies on DFC may lead to an optimum which is not sufficiently accurate in practice engineering [11]. Since the input power applied in plant is corresponding to the current state feedback [13], tiny fluctuations in the closed loop system may lead to huge deviations of response, and even system instability [14]. To deal with this troublesome problem, various techniques are proposed to handle such uncertain issues in servo mechanisms, such as adaptive control [15–17], fuzz control [18,19] and robust control [10,11,20–23]. Moreover, with the wide application of active control systems (i.e. servo mechanisms, active vibration control system and so on) in manufacturing industry, the safety problems are becoming more and more prominent. In recent years, the reliability assessment and reliability-based design of the active control system has aroused widely concern [24,25]. Venini et al. firstly introduced the reliability index to measure the effectiveness of an active control systems [26]. Spencer et al. proposed the FORM method to quantify the safety level of the stability for the closed-loop control system [27]. Taflanidis et al. presented the optimization model and the solution strategy to conduct the reliability-based design for active structural vibration control system [24,28]. Battaini et al. conducted the safety estimation of the controlled structures could be achieved by reliability measurements derived from SORM approximations [29].

It should be emphasized that the studies on the reliability of the active control systems mentioned above are based on the probabilistic frame which needs substantial amounts of sample data to precisely construct the statistic characteristics. Nevertheless, in some cases, the accurate statistic characteristics are extremely hard to be obtained by virtue of insufficient experiment data [30]. Under such circumstance, the probabilistic approach may not be eligible. Therefore, the concept of non-probabilistic reliability has attracted considerable attention in recent years, the original studies was presented by Ben-Haim et al. [31,32], and further developed and introduced into various uncertain problems in practical engineering by Qiu et al. [30,33,34], Jiang et al. [35–37], and Du et al. [38]. As for the non-probabilistic reliability of the feedback systems, Guo et al. employ the non-probabilistic reliability based design approach into the active vibration controller design problem [39]. Li et al. present an analytical solution strategy to evaluate the reliability of active control system by the non-probabilistic structural reliability measurement [40].

It is notable that the time-dependency effects of the dynamic response of the mechanisms should not be neglected. In the fields of time-dependent reliability, the first-passage theory is typically used to assess the structural/mechanism reliability with consideration of time-dependency effect [41]. Du et al. use the first passage theory to calculate the probabilistic interval kinematic reliability of the function generation mechanisms, and develop the reliability based synthesis procedure [42]. Jiang et al. firstly introduce the non-probabilistic convex process model into the structural dynamic reliability assessment issues [35]. Wang et al. develop the interval process to quantify the time-varying response of uncertain structures, and the solution strategies are further conducted [43]. Furthermore, Wang et al provide the time-dependent reliability measurement to quantify the dynamic safety of active control system with non-probabilistic interval variables [25].

Nevertheless, compared with the studies on the structure design problems, the studies on the time-dependent reliability based controller design for uncertain servo mechanisms under insufficient samples data is still rare. This paper aims to develop a novel non-probabilistic time-dependent reliability based design approach for controllers of the servo mechanisms. The rest of this paper is organized as followers: In Section 2, the concept of DFC for servo linkages is presented. In Section 3, the non-probabilistic time-dependent reliability analysis and reliability based optimization for the servo mechanisms are developed. The two numerical examples are presented in Section 5 to demonstrate the validity and effectiveness of time-dependent reliability assessment and reliability-based optimization, followed by some conclusions in Section 5.

2. Solution strategies for the controller design problems of deterministic servo mechanisms

2.1. Input speed trajectory melding based on Bezier curve

For a linkage mechanism with varying input speed, the crank is no longer undergoing a circular rotation with a constant angular velocity. Enlightened by Ref. [2], the desired displacement trajectory of the input link is defined by a nth-order Bezier curve which is given as

$$q_1^d(T) = \sum_{i=0}^{n} Q_i B_{i,n}(T), B_{i,n}(T) = \frac{n!}{i!(n-i)!} T^i (1-T)^{n-i},\ T \in [0,1] \tag{1}$$

where T is the normalized time which can be given as $T = \frac{t-t_0}{t_f-t_0} - [\frac{t-t_0}{t_f-t_0}]$, t_0, t_f and $[\cdot]$ are initial time, final time and Gauss symbol, respectively; Q_i and $q_1^d(T)$ are control points and desired angular displacement of input link at time t. Therefore, the desired angular velocity $\omega_1^d(T)$ and acceleration $a_1^d(T)$ of input link can be obtained by

$$\omega_1^d(T) = \sum_{i=0}^{n} Q_i \frac{\mathrm{d}B_{i,n}(T)}{\mathrm{d}T}, \quad a_1^d(T) = \sum_{i=0}^{n} Q_i \frac{\mathrm{d}^2 B_{i,n}(T)}{\mathrm{d}T^2}, \tag{2}$$

For the detailed formulation of $\frac{\mathrm{d}B_{i,n}(T)}{\mathrm{d}T}$ and $\frac{\mathrm{d}^2 B_{i,n}(T)}{\mathrm{d}T^2}$, see Ref. [2].