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Optimization of filter designs with dependent and asymmetrically distributed parameters

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Abstract

This paper presents a new statistical design method for maximizing the manufacturing yield of engineering systems for which the realizations of design parameters are assumed to be dependent random variables. Like in many practical situations, the method assumes that the joint distribution of design parameters is unknown and their marginal distributions can be estimated but are not necessarily symmetrical. This is a difficult problem to which little research has been devoted, other than using some brute force search methods. We use a Frank copula to construct the joint distribution of correlated random variables. Kumaraswamy density function is used to approximate their marginal distributions because of its flexibility and simplicity. The proposed method is based on the approximation of the yield integral over the largest rectangular hypercube (n-box) that is contained in the feasible region. It tries to maximize the yield by relocating and rescaling the box so that higher portion of the manufacturing yield is captured by this box. No integration is necessary since the yield of any given design is approximated by evaluating the cumulative distribution of the copula at the endpoints of the associated n-box. Finally, the actual yield of the optimal design is tested using Monte-Carlo simulation. This requires generating correlated random samples from the chosen copula distribution. One tutorial example and two practical design problems demonstrate the applications of the proposed method. Computational results show that the optimal designs significantly increase the manufacturing yield and this observation is verified using Monte-Carlo simulation.

Keywords: Filter design; Design centering; Tolerance design; Dependent design variables; Copula distribution

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1. Introduction

The topics of reliability-based and statistical designs have attracted a great deal of attention in recent years. The challenging task is to optimize the design of an engineering system under uncertainty, i.e., to find the best setting for a number of design parameters such that certain performance or quality characteristics of the product are met. In general, the source of uncertainty could be some noise in the input, variations in the system parameters due to fluctuations in manufacturing processes or material properties, and/or uncontrollable environmental conditions such as temperature or humidity. Statistical design methods are particularly concerned with randomness in the values of designable parameters which can be realized (produced) only with certain precision [1–4]. The choice of parameters nominal values and their allowable tolerances highly affects the system performance especially if random variations in the produced items are somehow dependent or correlated. This is certainly the case in micro-electromechanical systems and integrated circuits in which the correlation between the device parameters depends on their spatial locations. In the fabrication of integrated circuits, the impact of spatial correlation has been reported to account for up to 65% of total variations [5]. Furthermore, in comparison to the submicron dimensions of such devices, design tolerances could have a significant impact on the functionality of the system. Therefore, one has to take such variations into account during the design stage in order to optimize the robustness of the system design against process variations.

The parametric yield is a commonly used measure for the robustness of a design with respect to fluctuations in manufacturing processes [6]. Manufacturing yield is defined as the fraction of produced items whose output measures conform to the design specifications, within some acceptable margins. In other words, manufacturing yield could also be defined as the probability of a produced item satisfying the design specifications. In this sense, it could be related to the reliability of a design [7,8]. Deterministic design methods mostly ignore the uncertainty and attempt to determine the mean or nominal values of the parameters so that certain performance specifications are satisfied. However, this approach generates solutions that are, in general, very close to the boundary of the feasible region, defined by all design constraints. Thus, the resulting solution would be highly sensitive to small changes in the parameter values and could lead to a poor manufacturing yield [4,9]. This raises an important question of how to modify the design to increase the yield. Traditional worst case designs would consider the worst possible combination of all uncertain parameter values and thus are regarded as too conservative [10]. The objective of reliability-based design optimization (RBDO) or statistical design is to directly incorporate the impact of random fluctuations into an optimization model in a probabilistic sense. These methods search for a combination of expected values and tolerances of the designable parameters, which maximizes the manufacturing yield [4,7].

Most statistical design methods assume symmetrical (mostly Gaussian) distributions of random parameters and commonly ignore the possibility of having correlations (see for examples [2,11–13]). In such cases, the nominal design can be placed on the geometric center found by a design centering method. Worst case methods have an underlying assumption that random variables are independent and uniformly distributed. This simply translates the problem into finding the maximum volume rectangular hypercube (yield estimation box) that is contained in the feasible region [2–4]. Similar problems have been formulated using linear matrix inequalities [3,14]. This is done by shifting and scaling the tolerance body around the nominal values that is placed on the geometric center of the