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The Translation between Functional Requirements and Design Parameters for Robust Design

Simon Moritz Göhler[a]*, Stephan Husung[b], Thomas J. Howard[a]

[a]*Technical University of Denmark, Produktionstorvet Building 426, 2800 Kgs. Lyngby, Denmark*
[b]*Technische Universität Ilmenau, Department of Engineering Design, 98693 Ilmenau, Germany*

* Corresponding author. Tel.: +45 52 22 26 12. *E-mail address:* simogo@mek.dtu.dk

Abstract

The specification of and justification for design parameter (DP) tolerances are primarily based on the acceptable variation of the functions' performance and the functions' sensitivity to the design parameters. However, why certain tolerances are needed is often not transparent, especially in complex products with multi-disciplinary development teams. In those cases, tolerance synthesis and analysis get complicated which introduces ambiguities and difficulties for system-integrators and lead engineers for the objective decision making in terms of trade-offs but also in terms of an efficient computer aided functional tolerancing. Non-optimal tolerances yield potentials for cost improvements in manufacturing and more consistency of the functional performance of the product. In this contribution a framework is proposed to overcome the observed problems and increase the clarity, transparency and traceability of tolerances by analyzing the translation between the DPs and their influence on the final function.

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1. Introduction

Mechanical products and systems of all kinds are subject to variations in their parts' and assemblies' dimensions and forms, their materials, their use and their operation environment. However, despite these variations, products are expected to deliver their function and/or aesthetics to a predetermined extent and time to ensure customer satisfaction. To acknowledge the variation in the production phase, i.e. in manufacturing and assembly, part drawings usually contain tolerances on the single dimensions, forms and positions. In most cases these tolerances determine a large share of the cost of production but also of quality assurance. Tighter tolerances might require special production machinery, tooling, metrology equipment and drive the scrap and rework rate of a part; thus the effective analysis and assignment of tolerances as well as robust design can yield great cost saving potentials [1], [2].

The types and magnitudes of the tolerances, i.e. the size of the allowable ranges, are determined by the functional, technological and esthetical requirements of the product that shall be fulfilled. In highly complex (mechanical) products and systems that require multi-disciplinary development engineering teams (as for example jet engines that need specialists in Design, Fluids, Thermals, Structural Mechanics etc.), the relationship between tolerances and requirements often becomes complicated and non-transparent. This is especially the case when the outputs of one engineering discipline are inputs to another. When setting the tolerances, a whole patchwork of analyses of the influences of all kinds of variations develop where bonus tolerances and process capabilities are also considered in the allocation. Computer Aided Tolerancing (CAT) is utilized for tolerance synthesis and analysis [3], [4]. However, CAT is often limited to geometrical requirements like lengths, gaps and clearances as functional requirements [5]. The most common methods are tolerance chains and sensitivity analysis using experiments or simulations depending on the individual function. Due to the nature of multi-disciplinarity these analyses often stand separately and independently. An important challenge in a

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multi- disciplinary industrial application is that the engineers use different vocabularies for the requirement and problem specifications. Furthermore, for the specification of interface requirements often product characteristics (e.g. large width) are used instead of the required properties (e.g. high stiffness). As for the nominal dimensions that are being passed from discipline to discipline, the same happens to the tolerances and safety factors. The justification of tolerances is not very transparent making it difficult for system integrators and lead engineers to challenge the design and prioritize necessary additional analyses. Also, for drawings of parts that have been produced for years it is often the case that the justification of tolerances cannot be reconstructed and it is not understood what functions certain dimensions contribute to. In addition, the re-use of modules or components as part of a platform strategy may leave tolerance justifications running over multiple product lines. This all leads to a strong hesitation regarding changes to the parts due to unknown risks associated with those (see for example the GM ignition switch recall case [6]).

The translation between the design parameters (DPs) or external noise factors (NFs) and the functional requirements (FRs) is an established way to map the behavior of a product or system. The Robust Design Methodology (RDM) uses these transfer functions to derive sensitivities of functions to DPs and NFs to optimize the performance and predictability of the final product [2]. The setting of tolerances is directly linked to the sensitivity of the functions to the single DPs. RDM and the mapping between FRs and DPs are more or less explicitly done by the individual engineering disciplines. However, in the case of a complex and highly integral system, effects that go beyond a specific function or sub-function can be difficult to oversee. The mapping gets complicated and impractical in these instances making it difficult to have efficient tolerance design and allocation. “Information modelling is critical to the integration of design and tolerancing” [7].

The question arises of how the clarity and transparency of tolerances as well as their impact and severity on the final functional performance can be captured in a practical way.

In this contribution we address the encountered problem by proposing a framework on how to look at tolerances to support the specification and justification of tolerances for a robust design. Based on comprehensible decomposition and structuring of functional requirements and their design parameters a target-oriented communication between engineers of multi-disciplinary teams is supported. The framework enables the specification and justification of tolerances but also the setting of nominal dimensions across different disciplines and can give the basis for more advanced tolerance optimization within CAT.

2. Previous work

The idea of systematically mapping the dependencies of functions to design parameters and their tolerances is widely established in the engineering design community and is usually referred to as requirement or system decomposition. A framework that largely makes use of decomposition is Axiomatic Design (AD) by Nam P. Suh [8]. AD promotes not only the mapping between FRs and DPs but also the mapping from customer attributes (Customer domain) to the functional requirements and the mapping between design parameters and process variables in the process domain. The decomposition of the high level functional requirements and how these are addressed in the physical domain is realized by so called zigzagging between the functional and physical domain. With this, new evolving lower level requirements and design parameters are systematically established and a design solution generated. The function-means tree model as described by Hansen and Andreasen [9] works in a similar fashion arranging the functions and their realizations in a hierarchical manner. Söderberg and Johanneson [10] utilize function-means trees to detect potential tolerance chains to increase robustness. However, these techniques are more an idealized process that is often not practical, especially if the product is complex or solutions are being reused. Another framework that is more tailored towards the management of variation in design and manufacturing is the Variation Risk Management (VRM) framework by Thornton [11]. The framework is generally divided into three phases: Identification, Assessment and Mitigation. The identification of potential issues related to variation followed by the assessment of the associated risks as well as costs and the final mitigation of the issues with the most potential forms a holistic approach. In that way, trade-offs between design and manufacturing can efficiently and objectively be managed to improve the quality and cost of the final product. With respect to the systematical tackling of the issues, the identification phase comprising the collection of variation-sensitive requirements and the risk flow-down to understand the structure of the product are of high importance. “The risk flow-down is an iterative decomposition process that identifies a hierarchy of contributing assembly, subassembly, part and process parameters [12].” Dantan et al. [1] propose an information model capturing the causality of Manufacturing Process Key Characteristics and Part/Product Key Characteristics to manage manufacturing resources and tolerances. The House of Quality (HoQ) methodology in Quality Function Deployment (QFD) has a similar domain based structure as Axiomatic Design [13]. It maps the customer attributes through the parts and process domain to the production domain. The decomposition of the attributes is facilitated by relating the “whats” to the “hows”. “What” is the requirement and “how” is it addressed. The “hows” are turned into “whats” for every level of decomposition in a new “house”. The Integrated Tolerancing Process (ITP) as presented by Dantan et al. [7] addresses the functional decomposition of tolerances through geometrical requirements and decomposed functions. Howard et al. [14] proposed the Variation Management Framework (VMF) emphasizing the mapping of variation and sensitivities through the domains for robust design. Hansen [15] and Weber [16] presented further product and process representations describing the relationship between requirements and product characteristics considering external influences. Methods like FMEA (Failure modes and effects analysis) and RCA (Root conflict analysis) use decomposition