ROBUST DESIGN METHODOLOGY FOR THE DEVELOPMENT OF COMMERCIAL VEHICLE BRAKING SYSTEMS

[1]Kemmler, Stefan*, [2]Leopold, Tobias, [2]Fricke, Jens, [1]Bertsche, Bernd
[1]University of Stuttgart, Germany, [2]Knorr-Bremse Systeme für Nutzfahrzeuge GmbH, Germany

KEYWORDS – Robust Design Methodology, Axiomatic Design, SMART, Reliability, Air Disk Brake

ABSTRACT

Today's product requirements demand an ever increasing functionality for the same space and usually the same number of components. Thereby, the quality, reliability and robustness of these products should be preserved or even be increased. This target conflict cannot be solved without compromises. The research community between the Institute of Machine Components (IMA), University of Stuttgart, and the Knorr-Bremse Systeme für Nutzfahrzeuge GmbH is seeking for new solutions for these challenges. The new approaches for designing robust and reliable products are being implemented directly in a current development project of an innovative Air Disc Brake (ADB).

With "Systematic Method for Axiomatic Robustness-Testing" (SMART), reliability methods and the basic concept of Robust Design methodology are related to the Taguchi Method. SMART is based on three phases: System, Parameter and Tolerance Design; accordingly, the sample phases of VDA (Association of German Automotives) are used as milestones. In the System Design, SMART focuses on the decreasing complexity according to the functional dependences of the DPs, thus precluding early random failures. In the Parameter Design phase, SMART gives the developer an approach for modeling an adaptive simulation model (SIM-SMART). This model also enables the simulation of random and possible fatigue failures in addition to the nominally robust DPs. In the early stage of product development, reliability predictions are possible. In the iterative Tolerance Design phase, the final tolerance limits for robust and reliable products are defined with consideration of compromises in terms of costs, quality and technical feasibility.

With the application of SMART, a design concept of a new generation of an ADB with less complexity is created. The extensive functions for flexible function studies are modeled with the objective of SIM-SMART. Accordingly to this model, parameter studies for determination of the nominal adjustment levels can be performed and their random and fatigue failures modeled. In conclusion, more accurate reliability test strategies are recommended using the definition of tolerance limits. The cost aspect and technical feasibility are also taken into account.

So far, SMART has not been added to the iterative Tolerance Design phase. With this paper, the method is not only extended to this phase, but also sufficiently validated. In addition, SMART can predict and analyze random failures. With its three coherent and iterative phases, it is an as yet unpublished and unimplemented approach for designing even more robust and reliable products. Robust Design Methodology and reliability methods are fundamental building blocks for products with high quality requirements. SMART presents an approach to support the designing of robust, reliable, highly functional and innovative ADB.

TECHNICAL PAPER

INTRODUCTION

Today's requirements for products and processes are, in addition to low cost and development time, also potentials for savings for their production and processing with increasing functional performance. This means that the same or an even larger number of functions has to be fulfilled in a smaller space. Hence more functions are transmitted to the individual components, which in turn leads to an increased functional density, and thus to an increased complexity in the system. To accomplish this, serial system structures are generally implemented depending on the safety criterion. The demand for reliable and robust products and processes increases with these serial system structures and with the realization of high functional density. Consequently, a good compromise between requirements and technical feasibility must be determined: see Figure 1.

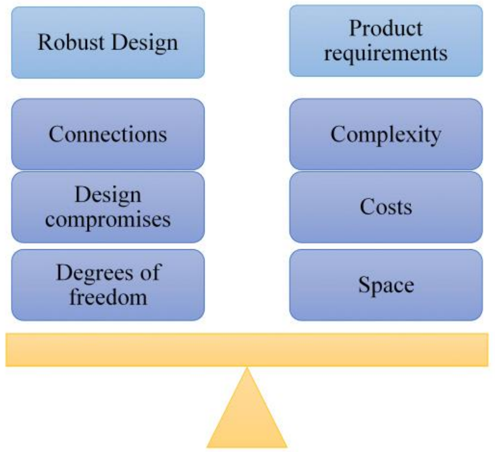

Figure 1: Scale between Robust Design and product requirements.

Due to the high density function within a system, correlations between Functional Requirements (FR) and their Design Parameter (DP) have to be systematically structured in the early stages of product development (Concept Phase) and their relationships and interactions have to be known. In addition, conscious and thus manageable compromises regarding the system complexity must be deferred to. Requirements such as less space and lower costs are necessary for economically successful products and processes. However, the focus should remain on the quality; it therefore forms the top priority in the development of robust and reliable products and processes. For this reason, design tradeoffs and the resulting restriction of the components' degrees of freedom have to be made.

STATEMENT OF THE PROBLEM

As a result of the increasing competition in industry and economy, the quality and time to market of a product or process has become a more central and important demand. The quality attributes can have different variations around their mean value and specification limits, which can lead to unexpected deviations from the required function. To control this effect, the Robust Design Methodology (RDM) by Genichi Taguchi (16) has been developed (12). According to (4) and (7), the quality of a product or process is essentially defined by the customers and their satisfaction. For this purpose, two aspects must be considered: the function of a product / process, and the ability of the product/process to perform this function at any time under the determined environmental conditions.

According to Park (13), there are three RDMs: the Taguchi Method (TM), the Axiomatic Design (AD) and the Robust Design Optimization (RDO). According to Genichi Taguchi (16), robustness is a state, whereas the performance of a product or process is minimally sensitive to the factors that cause variations and the one with the lowest possible manufacturing costs. Two steps have to be taken to find robustness (16): first, the smallest variation of the objective function has to be determined, and then the mean value has to be set to the required target value. In contrast, N.P. Suh (15) describes, in his approach of AD, a robust design as a design that meets his FRs despite large tolerances of the DPs and of the process variables during production and assembling. The third method is the RDO, which mainly deals with numerical solutions of the optimization of a design. For this purpose, the robustness aspect is already integrated during the optimization process (10). In contrast to the TM, the RDO has two main objectives: on the one hand, the robustness of the objective function has to be maximized, which is influenced by the tolerances of the design variables. On the other hand, it should guarantee that the entire tolerance range of the design variables all constraints are always satisfied (12). Despite the different approaches, all three methods have the main objective of RDM: the insensitivity of products and processes to variations (12).

However, the mentioned RDMs currently have a limited distribution in the industry, due to lack of information on methods of integration into the existing development process. In addition, there is little understanding of the use of the individual RDMs, and a lack of RDM techniques starting already in early product development phases and also in the integration of the aspect of reliability (1). General approaches of (5) and (6) exist, but no systematic approach to product development has been formulated.

SMART gives a systematic approach for designing robust products (8). This RDM was developed in the research cooperation between the Institute of Machine Components (IMA), University of Stuttgart, and the Knorr-Bremse Systeme für Nutzfahrzeuge GmbH and is described in the following chapter.

SYSTEMATIC METHOD FOR AXIOMATIC ROBUSTNESS-TESTING (SMART)

The need for a holistic and systematic approach, which efficiently uses the benefits of AD in the concept development, as well as the benefits of TM or RDO in the optimizing of parameters, derives from the missing RDM approach for the systematic implementation in the product development, as described in the previous chapter. This knowledge is the essential motivation for the development of the Systematic Method for Axiomatic Robustness-Testing (SMART)-Method; see Figure 2.

The Robust Design method SMART is aligned with the four chronological phases of the Product Development Process (PDP) of VDI (Association of German Engineers) Guideline 2221 (17). SMART also combined the System, Parameter and Tolerance Design phases with the PDP. The adaptive RDM provides an entry at any point in the development process, but with decreasing scope of design options (9).

SMART is launched, in principle, at the beginning of the Parameter Design with the construction of the P-diagram. If, however, there is no design concept at the beginning, a suitable design should be conceived initially as part of the System Design. Therefore, the Functional Requirements (FRs) are derived from the Customer Requirements (CRs) and the corresponding Design Parameters (DPs) are defined. Then the design matrix is set up for a clear dependency description and arranged with reference to the laws of reorganization in (11). Thus, the application of the independence axiom (15) is possible. If this is not

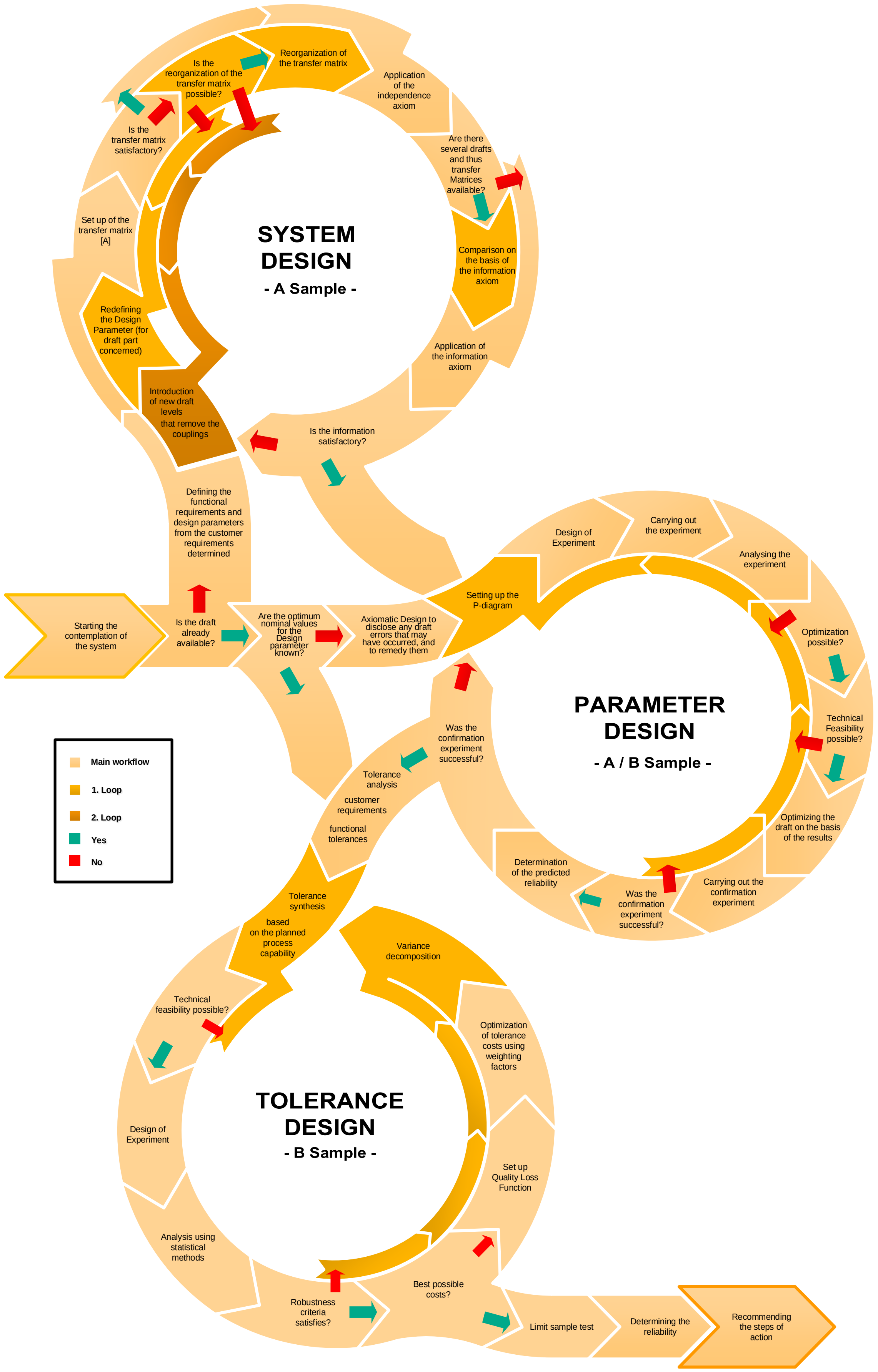

Figure 2: Systematic Method for Axiomatic Robustness Testing (9).

accomplished, new DPs are determined as appropriate, or a redesign has to be carried out.

In the next step, the analysis and the comparison of the available design alternatives are performed by the information axiom (15). If an adequate design using its information content is found, the next phase, the Parameter Design, and the deployment of the P-diagram, (8) begins.

The target of the Parameter Design phase is to determine a robust and reliable design, in terms of its nominally adjusted DPs with respect to the objective function. If there is already a design at the beginning of SMART, using AD is nevertheless recommended in this context as a system analysis tool to uncover any opportunities for improvement and potential weaknesses of the design. All required parameters are divided in control factors, signal factors, confounding factors and objective function in the P-diagram by their features and for the subsequent design of experiment (DOE). The knowledge of the previous AD can be helpful thereby and, for example, already provide information about which parameters are to be considered critical and need to be examined in the DOE. The implementation of the statistical tests can be done classically or by RDO, which should be decided on for each specific problem. For this reason, SMART provides open space to the developer. The evaluation and clarification of whether an optimization of the design can be accomplished and whether it is technically feasible are made afterwards. If both requirements are met, and the subsequent confirmation experiment is successful, first reliability predictions in the form of random and fatigue failure (2) can be determined. If these match with the required reliability parameters, the Tolerance Design phase follows.

After an adequate reliability prediction, or if optimal nominal parameter levels for the DPs are already present at the beginning of SMART, the optimal and robust tolerance limits are determined in the subsequent Tolerance Design, and the actual mean value and the variance of the objective function considering the cost aspect and the technical feasibility are defined. DPs, which have no significant performance fluctuations with regard to the target size, can be expanded in their tolerance limits. DPs with significant performance fluctuations, however, are constrained accordingly. If the DPs and the resulting objective function are clearly defined, confirmation experiments are conducted: Which makes it possible to make additional reliability tests. If the design accomplishes the required reliability requirements, then further guidance can be defined.

ADJUSTER UNIT

Trucks in Europe are nowadays equipped almost entirely with air disc brakes (ADBs) (3). A defined clearance between brake disc and brake pad has to be present for a reliable braking function. In this case, this clearance should not be set too small, so that a constant grinding or even an overheating of the brake will be avoided. In addition, the clearance must be set at a sufficiently large interval so that tumbling of the brake disc does not lead to contact and thus to uneven deterioration.

The clearance must also be adequately protected against thermal expansion of the components. The clearance should be designed in such a way that all possible working conditions of the vehicle are covered. ADBs have usual ranges from *0.5 to 1.1 mm*. The adjustment path per brake stroke is shown in Figure 3 and is defined as follows (3):

$$h_N = f_N(h_{idle} - s_{cc}) \tag{1}$$

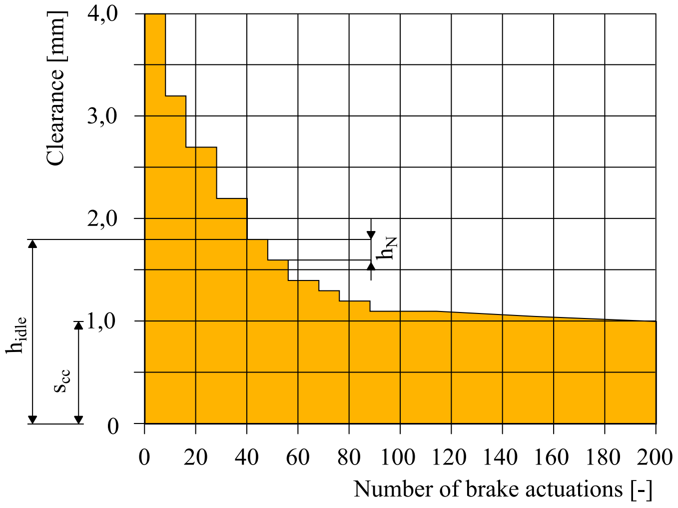

Figure 3: Adjustment speed according to (3).

The constant adherence to the nominal value of *0.8 mm* within the specification limits is implemented by a mechanical adjusting unit. The active adjustment process only takes place if there is no contact between the brake pad and the brake disc. Once a braking force on the threaded spindle and on the brake pads acts on the brake rotor, each adjusting movement is stopped. The actuator for the adjusting movement is the lever, which is coupled by a positive connection with the adjuster. A defined brake lever travel is executed without any adjustment upon each brake actuation.

The drive movement of the lever only acts on the adjuster after a certain amount of clearance, and a drive torque is initialized. The defined stroke (h_{idle}) is referred to constructive clearance and essentially determines the clearance that has to be adjusted. The amount that is adjusted during the actuation of the brake (h_N) is proportional to the difference of the stroke (h_{idle}) and the constructive clearance (s_{cc}), which is referred to as excess travel, and adjustment factor of the brake (f_N), see Equation 1. The adjustment factor (f_N) is an important quality criterion of an adjusting unit and should be defined in addition to the constant clearance as an objective function in the development of adjustment units. It is a measure of the speed at which too big clearance over the number of brake actuations can be corrected (9).

SMART SYSTEM DESIGN

At the beginning of the System Design phase, defining all requirements holistically is strictly required, both from a customer's point of view and from the company-internal perspective.

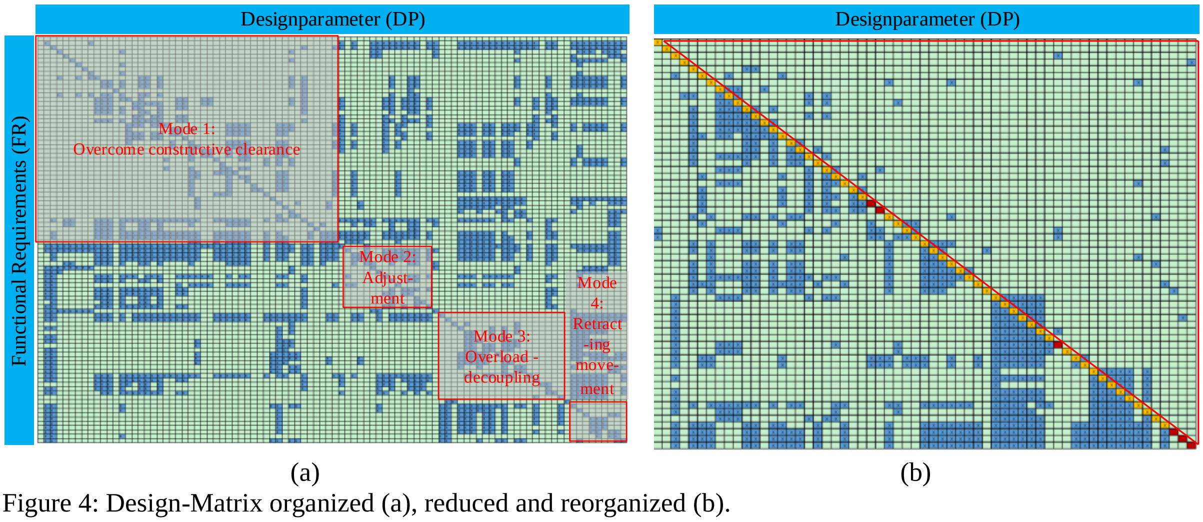

Figure 4: Design-Matrix organized (a), reduced and reorganized (b).

This will be done with a kind of function requirement specification, in which the parameters are divided in control factors, signal factors and confounding factors. A classification of the parameters with their specification limits in the P-diagram is useful for a better overview of all factors. In terms of a functional block diagram, a system-based approach is before the design matrix is set up is advantageous. In this diagram, all components within the system boundary “Adjuster” are shown with regard to their connection property as well as their degrees of freedom. The consideration of the cause-effect relationship is, as a result of the operating modes, essential for the simulation strategy out of the Parameter Design and for arranging the design matrix.

This classification into the various operating modes in the diagram of the cause-effect relationship gives a very clear understanding of the cause-effect relationship of the individual components and their functions among the components of each mode of operation. The different operation modes of the adjuster are listed below: overcome the constructive clearance, brake press (adjustment), overload mode (decoupling), release brake (rear rotary motion) and service function. The latter mode occurs only during maintenance of the brake and therefore is not applicable in the regular operation of the adjusting unit (9).

After the determination of the operating modes and of the top level of the design matrix, these can be arranged. A viewing depth to the third or, at most, the fourth level, is advisable, which means that the quantified DPs out the function requirement specification should be in the last level, e.g. the maximum overload torque. It appears that such a complex product, with its high demands, results in a very large and confusing matrix; see also Figure 4a.

It can be seen that the individual operation modes are stretched on the diagonal. In the horizontal and in the vertical, the dependencies of the FRs, and of the DPs, respectively, are marked with a blue field. In this matrix structure, however, is it not possible to infer a precise statement of the complexity of the system. Accordingly, a reorganization is performed with the algorithm according to (11). With the reorganization of the full design matrix, the number of coupling elements is significantly reduced. In addition, the clustering facilitates the interpretation of the matrix, because the functions belonging together are close to each other and are not widely scattered; see Figure 4b.The individual outliers above the diagonal must be considered in the next step. If these are acceptable, the independence axiom is satisfied. Since it is a single concept, the information axiom is omitted here and, in accordance with the definition of SMART, the Parameter Design phase can be skipped to.

SMART PARAMETER DESIGN

The new adjustment unit was developed with the use of SMART. Because of the high simulation effort, a new simulation method (SIM-SMART) was designed and implemented. This adaptive simulation method is published in (9) and will not be explained in detail. As an example, to investigate the robustness of the adjuster, 43 parameters, 32 control factors and 11 noise factors were defined from the previous sensitivity analysis. Based on the simulation strategy, the 32 control parameters are composed of 7 Brake-Parameters (BP) and 25 Adjust-Parameters (AP). An exclusive consideration of the adjuster with the objective function constant clearance or adjustment speed does not make sense, because the clearance is composed of the bridge way of the brake and of the adjustment path of the adjuster and thus contains parameters which are located outside the system boundary of the adjuster.

For a high number of parameters, an optimization and robustness analysis by TM is recommended. The prerequisite for using the TM is present, since there is no high mixing (significance and effects between the parameters). As a result of any existing non-linearities,

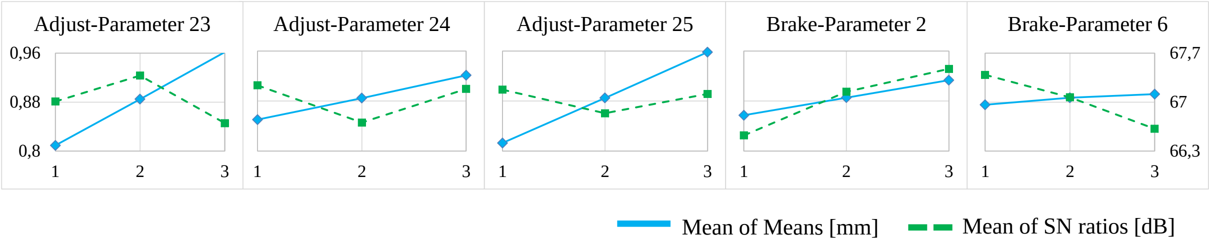

Figure 5: An extract from the results of the nominal control factors out of the Taguchi-DoE.

the Taguchi experimental design for the internal field (control factors) is planned on three levels ($L_{81}(3^{32})$). Following the principle of robust design, the external field is interpreted (noise factors) on two levels ($L_{12}(2^{11})$). This results in a number of trials, for a total of $n = 972$. SIM-SMART takes about $t_{sim} = 4\ min$ for an execution, which results in a total time of $t_{sim\_ges} = 64.8\ h$. In comparison, a pure FE-simulation of the adjuster with the same number of attempts has an execution period of $t_{sim\_ges} = 162\ d$.

The analysis of the experimental design takes place after TM by considering the variance of the nominal parameter settings. For this purpose, the target value problem II nominal-the-best signal-to-noise ratio is applied (14) and is defined as follows:

$$S/N_{nom} = -10\ log(s_i^2) \tag{2}$$

In Figure 5, both the mean of S/N ratios and the Mean of Means of the individual parameter levels of the control factors are shown. With the exception of the significant APs 23-25 and BPs 2 and 6, all control factors are placed at the level with the maximum S/N ratio (lowest diffusion), since their mean value changes marginally. With the significant parameters, a compromise between high S/N ratio and mean value needs to be deferred to. The exception is the AP 23, which has its smallest variation in the area of the mean value. BP 6 should be set to the lower parameter level 1 and BP 2, despite the greater dispersion, the average parameter level 2 should be set, analogous to the AP 24 parameter level 3. Due to the highly fluctuating mean value of AP 25, the parameter level 2 should be set, although it has the largest variation. The difference between the minimal and the maximum specification limits of the adjustment speed and the clearance are shown in Figure 6. The spread of the DPs, which are given to the Parameter Design phase, is brighter and outside of the required limits. A possible smaller

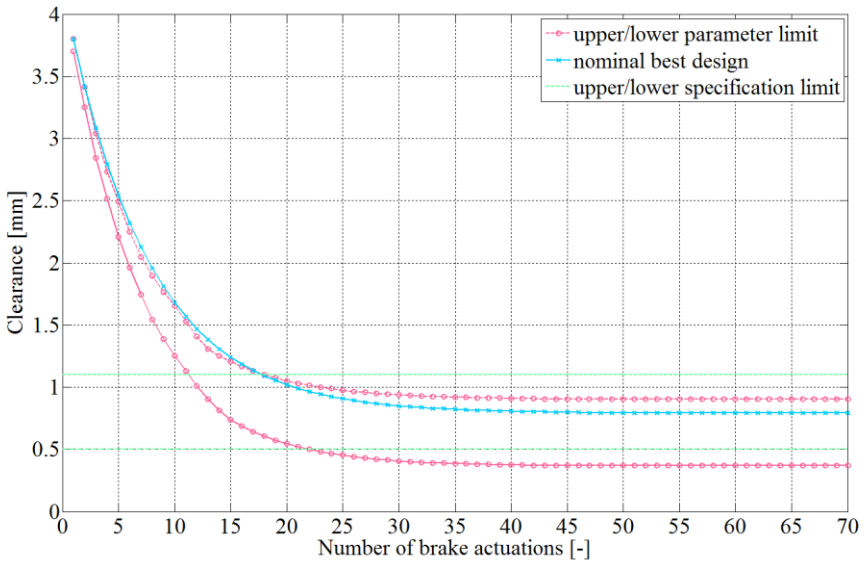

Figure 6: Comparison of the adjustment speed and clearance of the given DPs to the Parameter Design phase and the nominal DPs found at the end of the Parameter Design phase.

spread within the required limits of the adjustment speed and of the clearance was found, based on the nominal parameter levels of APs and BPs; see above.

SMART TOLERANCE DESIGN

After the subsequent experiment confirms the nominal parameters levels, a nominal optimal design is defined, which has qualitative the lowest variations and reaches the predetermined target value. It can now be entered in the Tolerance Design using SMART and the existing variations in the system can be described quantitatively. In these last iterative phases, two steps are performed; see Figure 2. In the first step, the robust design, in which the actual variation is conformed to the desired variation with the statistical experimental design and the variance decomposition, is to be determined. This is implemented by means of evaluation factors for the production costs in combination with the variance decomposition. The last step is the integration of the cost aspect and its optimization (cost and loss analysis) using Taguchi's Quality Loss Function. The process of both steps is separated as the primary goal: the development of a robust product. At the beginning of the Tolerance Design, the production possibility must be clarified and compared with the final frontier model experiment. If successful, the loop of Tolerance Designs can be exited. A testing strategy, which confirms the reliability required in the ideal case, is defined on the basis of given test potentials.

DISCUSSION AND CONCLUSION

The integration and association of AD with the TM in SMART make it possible to offer a structured approach at the functional level in the early development phase. With AD, functional dependencies between DPs and FRs can be demonstrated at an early stage, which possibly lead to complex system structures and, consequently to failure of the product. In addition, the functional analysis of the components in the system gives the developer a system analysis in hand, which in turn can be used for other applications, such as FMEA. A preliminary comprehensively-developed FR specification is essential, and should be present during the entire development phase. Using this and the AD, all necessary parameters for a robust and reliable design can be defined at an early stage and can be shown systematically in the P-diagram, which is the basis for the parametric study. Based on the P-diagram, a simulation model must be modeled in the Parameter Design phase, which at most captures all the parameters and FRs and provides a small computing time.

Without this groundwork, the subsequent parametric study can not be carried out consistently and efficiently. SIM SMART gives a very good possibility of adaptively adding potentially complex simulations and thus enables a simultaneous engineering. This has the distinct advantage of enabling early checks of the FRs of the product. Another important point for modeling the simulation model is to define the simulation strategy, which must be defined prior to modeling. In the presented example of the adjuster, the aim of achieving a constant clearance and a high adjustment speed is not possible without considering the overall brake. Thus, the system limit has to be extended here.

As SMART points out in its approach, a specific determination of the applicable method is not useful. SMART specifies that the developer can consider his appropriate free space on his own, and which methods he posits, using the procedure in the Parameter Design, by TM or RDO. However, SMART is a basic systematic structure of the development method in line with the robust design ideas. Although the current stage of the project, the RDM SMART, is not complete, it can be used as a complete development method based in successful preliminary studies.

OUTLOOK AND FURTHER RESEARCH

In the current state of the project, the methodological approach of Tolerance Design is implemented further by SMART after the successful validation tests or confirmation experiments. The method has been successfully implemented on individual components of the brake, for example through the overload clutch of the adjuster. Thus, it is predicted that the method can be successfully performed on the brake. In addition, some preliminary work, such as clarification of the manufacturing processes and costs, are done as indicators.

Further research work is related to the implementation of reliability in terms of the failure modes analysis, the fatigue testing (both by simulation and real terms) and the integration of random failures in the Parameter Design. In addition, early reliability statements are to be integrated in the early System Design phase. Finally, after a successfully- completed Tolerance Design, SMART should be validated as an integrated development methodology for the robust design idea.

REFERENCES

(1) Bergman B., de Maré J., Lorén S., Svensson T., “Robust design methodology for reliability – Exploring the effects of variation and uncertainty”, Wiley, 2009

(2) Bertsche B., “Reliability in Automotive and Mechanical Engineering”, Springer, 2008

(3) Breuer B., Bill K. H., “Bremshandbuch – Grundlagen, Komponenten, Systeme Fahrdynamik”, Springer, 2012

(4) Fowlkes W. Y., Creveling C. M., “Engineering methods for robust product design – Using Taguchi Methods in Technology and Product Development”, Addision-Wesley, 2009

(5) Hasenkamp T., Adler T., Carlsson A., Arvidsson M., “Robust Design Methodology in a Generic Product Design Process”, Total Quality Management, Vol. 18, p. 351-362, 2007

(6) Hasenkamp T., Arvidsson M., Gremyr I., “A review of practices for robust design methodology”, Journal of Engineering Design, Vol. 20, p. 645-657, 2009

(7) Juran J. M., Gryna F. M., “Juran’s Quality Control Handbook”, McGraw-Hill, 1988

(8) Kemmler S., Bertsche B., “Systematic Method for Axiomatic Robustness-Testing (SMART)”, Proceedings of the International Symposium on Robust Design, p. 101-112, 2014

(9) Kemmler S., Dazer M., Leopold T., Bertsche B., “Method for the development of a functional adaptive simulation model for designing robust products”, 11th Weimar Optimization and Stochastic Days, 2014

(10) Könning M., “Kombination von Optimierung und Robustheit in der Simulation mechanischer Systeme”, 2nd Weimar Optimization and Stochastic Days, 2005

(11) Moreno Benevidas E., Garcia Rodriguez L., “Extended algorithm for design-matrix reorganization”, Proceedings of the 6th ICAD, 2011

(12) Park G.-J., “Analytic methods for design practice”, Springer, 2007

(13) Park G.-J., Lee T.-H., Lee K. H., Hwang, K.-H., ”Robust Design: An Overview”, AIAA Journal, Vol. 44, p. 181-191, 2006

(14) Phadke M. S., “Quality engineering using Robust Design”, Prentice Hall, 1989

(15) Suh N. P., “Axiomatic design – Advances and applications”, Oxford University Press, 2001

(16) Taguchi G., “Taguchi’s Quality Engineering Handbook”, Wiley, 2005

(17) VDI – Verein Deutscher Ingenieure e.V., “VDI Guideline 2221”, Beuth Verlag, 1993