Design Guidance for Robust Design using Load-Strength and Design of Experiments

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Abstract

The short product development cycle and the increased demand of robust, safe and reliable design has made the Test Analysis And Fix (TAAF) method obsolete. Closing the feedback loop on a design from field return (FRACAS) takes years. Closing the feedback loop from testing takes months. Therefore a modern design has to build in robustness, safety and reliability during the design process. The paper describes how the Load-Strength theory and design of experiment (DOE) can be used to develop design guidance for a robust design. The influence of safety margin and loading roughness is described together with repeated loads. Real examples of design guidance for robust design are shown.

1. Introduction

Robustness is defined by IEEE as “the degree to which a system or component can function correctly in the presence of invalid input or stressful environmental conditions” (IEEE, 1991). The designer has to find a feasible design and optimize it within the constraints of specifications, environment conditions, costs and schedule. The system design will not be covered in this paper. After the system design a number of modules or assemblies will normally be defined. The detail design will then be made, designing modules by combining components and design details.

It will seldom be possible to optimize the system design or the detail design analytically for example by a response surface. Modern software allows response surface optimization for a larger number of parameters or constraints, but this will normally only allow a partial analysis. Therefore the designer has to use an iterative and heuristic design process. The robust design philosophy is concerned with taking into account variations in the manufacturing, environmental and usage conditions. For this there exist a number of methods. Some of these will be discussed in the following, and practical examples of their application are shown. The designer will normally have to apply and combine several methods for a given design task. This means that normally no single method will be enough to ensure a robust design for example used as a Key Performance Indicator (KPI) for the project.

2. Problem statement

A well known model for the design process is the V-model (Figure 1). The system specification is broken down into modules (assemblies) by interface specifications, which are again broken
down in component (design details) specifications. This consists of the left part of the V. On the right part of the V, the finished design is tested first on component/design detail level, followed by integration tests on module/assembly level before the final tests at system level.

3. Existing Approaches

Some 20 years ago the design philosophy in most companies was the Test Analyze And Fix (TAAF) method where the design was tested and after that the necessary few changes and improvements were made. To day this method is considered obsolete, since it takes too long time and with the high reliability and robustness requirement of to day's market it is not possible to verify the requirements by testing alone. Robustness and reliability have to designed into the product, not added in the test phase.

![Figure 1. The V-model - Feedback delays](image)

3. Proposed procedures

In an iterative and heuristic design process the designer need to have feedback on the performance of a proposed design. Therefore the time to close this feedback loop is critical. The feedback time from the field is typically years. The feedback time from system test, integration test and component test is typically months. Therefore it is not possible for the designer to make many design iterations. But at the bottom of the V, is the design process before any hardware is produced. It is proposed to make a large number of design iterations here. With a short feedback time more design iterations can be made, and the final design can be more robust and reliable. A number of methods are possible for this purpose (Arvidsson and Gremyr, 2008). These methods can often close the feedback loop in minutes to days. Examples are: Design review (IEC 61160), Failure Mode Effect Criticality Analysis (FMECA) (IEC 61160), Fault Tree Analysis (FTA) (IEC 61025), Design of Experiment (DOE) (IEC 60812), Finite Element Analysis (FEM), Tolerance Analysis (IEC 61160) and (Ebro, Howard and Rasmussen, 2012), Load-Strength analysis (Carter, 1972), Analysis of degree of freedom [9], interface analysis (Ebro, Howard and Rasmussen, 2012) and Monte-Carlo analysis (Dubin, 2000). Some of these methods will be discussed in the following. It is proposed that design guidelines are developed for critical design details, based on analysis, simulation and design of experiment (DOE). Practical examples of such guidelines will be described in the following.

4. Guidelines based on design of experiment (DOE)

Design of experiments was used to develop the design guidelines described in Clause 8. Most Design of Experiments requires hardware, but to day DOE is often used to reduce the number of simulations made (for example FEM simulations) (Jones and Johnson, 2009) Even if hardware is required DOE can be made on design details to save time and resources. For robustness the DOE is often combined with the Signal-Noise (S/N) philosophy of Taguchi (Phadke, 1989) and (Singh et al.) The Signal-Noise philosophy regards the parameters that the designer
can change as the signal, and the parameters that the designer can not influence, for example environmental and usage parameters as noise. The concept S/N is well known from electronic design. If the signal noise ratio is high there is a strong signal relative to the noise. This means that the design is robust. If however there is a weak signal in a strong noise, the design is not robust. As in electronic design the S/N ratio is measured in dB. Based on a DOE the S/N ratio of different design options can be estimated, and the design with the largest S/N ratio can be chosen. The calculation of the S/N ratio depends on whether the required function has to be maximized (for example output), minimized (for example power consumption) or be close to nominal (for example precision). In the following an example shall be given of such a DOE.

The design was a product where 3 prototypes were finished. Testing had shown unsatisfactory performance. The project team could not agree on the reason. They listed 15 factors that may all influence the problem. It was decided to make a DOE to screen for the important factors. For screening purpose a DOE of a fractional design is often used. In this case a Taguchi L16 test plan was selected. It allowed 15 design factors to be varied, each on two levels. The test required 16 test items. By manufacturing some new parts, and change adjustments it was possible to modify the 3 prototypes to create 16 different test configurations. 3 parameters of performance for the product were recorded during the test. To verify the result the test was repeated with 2 of the performance parameters. In total 5 results for each test run. The test was performed during the weekend.

![Image](image_url)

*Figure 2. DOE and S/N ratio used for robust design – Level 1 is A1, B1, C1,...,O1.*

To report the results in a condensed format the 15 design factors were named A to O. For each the 5 performance results were plotted as 5 columns above the x-axis. Since the test was made with repetitions it was possible to compute the S/N ratio in dB. This was plotted as columns downwards from the x-axis. This means that the strongest design parameters are the highest columns upward from the x-axis, and the most robust design the largest columns below the x-axis. It could now be concluded that the strongest design parameters were A, G, I, J, K and O while C, E, F, H, M and N only had a weak influence on the performance. Fortunately the optimum combination was also the most robust, so no trade off was required. It was possible to define the optimum and most robust design combination as A2, G1, I2, J1, K1 and O1.
5. Guidelines based on tolerance analysis

A major factor in robust design is the variation of dimensions due to the manufacturing processes, as expressed by tolerances. There are different methods to optimize tolerance for example the Taguchi loss function (Phadke, 1989) that use DOE to find the optimum tolerances. Often several tolerances have to be combined to evaluate the influence on the function. This can be done using analytical methods as for example the square root of the sum of the standard deviations squared. For more complicated combination of tolerances, a Monte-Carlo simulation can be used.

To achieve a robust design the tolerances should be selected so they have the least influence on the output parameter as shown in Figure 3. The influence of dimension G on the output parameter. V(G) is shown as the slope of the straight line.

![Figure 3. The sensitivity of the output parameter V(G) depending on the tolerances of G](image)

A more general method is to compute the partial derivatives of the design function (Morrison, 2009). In this way it is possible to estimate the influence of each parameter on the output parameter. It is then possible to tighten the tolerances selectively on the dimensions that have the largest influence and relax the tolerances on the rest of the dimensions. This method was used in developing the design guidelines described in Clause 7.

6. Design guidelines based on Load-Strength

For mechanical failures the Load-Strength method was developed (Carter, 1972). The method has since been used also for electrical design. The idea is that the design will fail in the moment when the load (L) is larger than the strength (S). But the strength of the product is not one number, but a distribution due to variations in tolerances, material parameters and processing. Also the load can be modeled as a distribution. The load varies due to conditions of use and environments. It is now evident as shown on Figure 4 that the area of overlap between the two curves is proportional to the probability of failure. For the general case in Figure 4 the reliability (R) and the probability of failure (F) can be computed as a double integral as shown in Figure 4. Software programs like Weibull++ can solve this integral for Weibull distributed load and strength (L-S) curves. For description of the Weibull distribution see (IEC 61649). For power transistors $\beta=1.2$ and $\beta=1.8$ has been observed for the strength and $\beta=1.4$ and $\beta=3.1$ for the load.
If both the load and the strength distributions are normal distributions (Gauss distributions) the computation is easier as shown in Figure 5.

A.D.S. Carter (1972) developed the Load-Strength method to include fatigue. See also Keciceogolu (1972) and O’Connor (1995). Carter described two extreme cases of L-S curves based on two parameters Safety Margin (SM) (see Figure 5) and Loading roughness (LR) as shown on Figure 6. These two cases are discussed in (Loll, A).

A constant load have a loading roughness of zero (here called case A), while a design with constant strength have a loading roughness of 1 (here called case B). All real designs must be somewhere between case A and case B.

For repeated loads Case A has a constant reliability over time (wear and fatigue is not considered). For components connected in series (the system only function if all components func-
tion), the reliability of the system decreases rapidly with the number of components. For case B the reliability with repeated load decrease with the number of loads. But for case B it is possible to connect many components in series without decreasing the reliability. Carter performs a simulation of designs with different SM and LR together with different wear out function like corrosion and fatigue (Carter, 1972).

![Figure 7. Design margin and degradation (damage accumulation)](image)

A general design rule for Load-Strength is that there should be sufficient margin between the Load and the Strength distribution not only at zero operating time, but also by the end of the useful life, taking into account wear, corrosion and fatigue (see Figure 7). But the problem is how much margin is enough. The margins can be identified using the HALT test method (Otto, 2004) to identify the weakest part of the design and make them as strong as the rest of the design. The advantage of this is that it is not needed to increase the margin for the whole product, but only for those few components / design details (typically 2-3) that are weaker than the rest.

Carter [8] has developed a theory for selecting the necessary margin. The method is also described by O’Connor (1995). The failure rate is plotted on a logarithmic scale as function of the safety margin (SM) and loading roughness (LR)as shown on Figure 8.

![Figure 8. Failure rate as function of Safety Margin (SM) and Loading Roughness (LR)](image)

It can be seen that the curve can be divided into 3 areas. For low SM the failure rate is too high. In the next area the design is not robust – the failure rate varies rapidly with the SM. In the area to the right however the failure rate is very low (the y-axis is logarithmic). To make a robust design the designer has to place the design just to the right of the curve. It is possible to draw several curves for different loading roughness (LR) as shown on Figure 8. O’Connor [15] also has curves for Weibull distributed L-S curves. The method is very promising, but more research is needed to make it practically applicable.
7. Design Guidelines for a mechanical mechanism using Load-Strength

The Load-Strength method can also be used to design moving mechanical mechanisms (Loll, B). Bang & Olufsen needed urgently to introduce a feature that would permit a turntable to automatically detect the diameter of the record and select the rotation speed accordingly. It was decided to use the weight of the record instead of the diameter. Different records have different weight, so the weight distribution of small records was measured. The spring that had to lift the record also had a force distribution. Further the switch that had to change the rotation speed added a friction with a distribution. That meant that three distributions had to be taken into account for the design. The design was made by calculating the torque around the axis of the lifting mechanism taking into account the standard deviations of the distributions as described by Morrison (2009) (Figure 9).

To calculate the influence of the standard deviations the computation rules for combining uncertainties for sum as well as logarithmic design functions were used (Loll, B). The calculation showed a failure probability of 0.36%. The design was a success on the market.

![Figure 9. Load-Strength used to analyze a mechanical weighing mechanism.](image)

8. Design Guidelines for screw towers using DOE

Bang & Olufsen had big problems with screw towers in plastic. The self threatening screws could sometimes not be screwed fully in during production. But in other cases the thread was destroyed so that the screw was loose. This caused it to fall out causing the printed wiring board (PWB) to be loose. Often the loose screw caused short circuit or other function failures. To solve the problem it was decided to make a DOE on test towers in cooperation with the screw manufacturer. Based on this DOE it was possible to set up design guidance for screw towers. The guidance was made as parameter design on a computer so that the designer could specify the dimensions and immediately have the correct drawing together with calculated screw torque and strength of the screw tower (Figure 10).

![Figure 10. Design guidelines for a screw tower](image)
9. Design Guidelines for a plastic snap lock using Finite Element simulation

Another problem for Bang & Olufsen was the plastic snap lock for the remote controls. The snap lock kept the printed wiring board (PWB) in place, but it also had to take up the load when the customer pushed the buttons. The design is shown on Figure 11.

![Flexible snap-lock and Fixed stop](image)

*Figure 11. Design guidelines for a plastic snap lock*

The feed back from the market showed that the snap locks were breaking. The management ordered the snap locks to be strengthened, but this only made the problem worse. Finally it was realized that the tolerance of the PWB was ± 0.2 mm. So the snap lock should be made weaker and not stronger (stiffer).

The stress in the plastic material was calculated using basic analytic equation (cantilever beam). Further the stress in the snap lock was calculated using a FEM program and finally the stress was measured using a strain gauge. It can be seen on Figure 12 that the results are very close. It is very important to verify simulations with measurements.

The calculation shown on Figure 12 show that within the constraints of the PWB thickness and tolerances and the fatigue limit of the plastic material a robust design was not possible. It was therefore decided to divide the function into two different design features. One was flexible snap locks that should just keep the PWB in place. The other was ridgid supports that should take up the force when the customers pushed the buttons (see Figure 11).

![Stress, tolerances and fatigue limits](image)

*Figure 12. Stress, tolerances and fatigue limits for the snap lock*
10. Design Guidelines for plastic moulding using Load-Strength

A major question from the designers at Bang and Olufsen was how much safety factor should be used when designing plastic parts. To give design guidance a number of simulations were made based on moulded test parts. Based on strength measurements and literature it was possible to give guidance for safety factors for different moulding conditions as described in (Loll, C).

11. Conclusion

Modern products require robustness and reliability to be designed into the product and not added by testing. Testing should only confirm the result of the design. Tolerances can be optimized using DOE and the Taguchi loss function or the partial derivatives of the design function. DOE can be used based on testing of design details, combined with the S/N ratio to optimize robustness. DOE with fractional design can also be used to reduce the number of FEM or Monte-Carlo simulations. Fractional design can further be used to identify the most important design parameters (screening test). It is proposed that the companies develop design guidance for the most important and critical design features in their products. Such design guidance will help the designer make more design iterations. A number of real examples of these methods were shown. Load-Strength analysis can be used to estimate the needed design margin for robustness of a static or moving design. More research is needed to make the method of robust design based on the SM and LR parameters applicable in industry.

References


IEC 61160 Design Review – International Standard

IEC 60812 Failure Mode and Effect Analysis (FMEA) – International Standard

IEC 61025 Fault Tree Analysis (FTA) – International Standard


IEC 61649 Weibull Analysis – International Standard


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