Robust Design & Reliability Engineering

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Abstract

Robust Design (RD) Methodology is discussed for hardware development. Comparison is made with reliability engineering (RE) tools and practices. Differences and similarities are presented.

Proximity to ideal function for robust design is presented and compared to physics of failure and other reliability modeling and prediction approaches. Measurement selection is shown to strongly differentiates RD and reliability engineering methods. When and how to get the most from each methodology is outlined. Pitfalls for each set of practices are also covered.
Many Design methods & Interfaces
RD ≠ Reliability

Robust Design
- Layout
- 6σ
- Tolerance Design
- Ideal Function
- Response Tuning
- Flexibility
- Lean
- Quality Loss
- Reuse
- S/N
- RSM
- Online QC
- Parameter design
- Generic Function
- POE
- CBM
- Warranty $
A systematic engineering based methodology (which is part of the Quality Engineering Process) that develops and manufactures high reliability products at low cost with reduced delivery cycle. The goal of robust design is to improve R&D productivity and reduce variation while maintaining low cost before shipment and minimal loss to society after shipment.

*Dr Taguchi, who died this year, always used to say “let’s find a way to improve reliability without measuring reliability”*
Robustness is...

“The ability to transform input to output as closely to ideal function as possible. Proximity to ideal function is highly desirable. A design is more robust if ratio of useful part to harmful part [of input energy] is large. A design is more robust if it operates close to ideal, even when exposed to various noise factors, including time”

Reliability is...

“The ability of a system, subsystem, assembly, or component to perform its required functions under stated conditions for a specified period of time”
**RD Noise Factor Definitions:**

Factors that disturb the function, which are difficult to control, or too expensive to control.

- External noise factors include temperature, humidity, dust, vibration, contaminants,...

- Unit-to-unit variation from manufacturing processes.

- Deterioration, as time passes.

Selection of noise factors and levels is a prediction of how device will be used downstream. Noise factors are used for upstream, midstream and sometimes downstream experimentation.
<table>
<thead>
<tr>
<th>Robust Design</th>
<th>HALT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantitative</td>
<td>Qualitative</td>
</tr>
<tr>
<td>‘Customer from hell ‘ prediction , with compound noise factors</td>
<td>Highly elevated stress levels for Temp, Vibration , voltage</td>
</tr>
<tr>
<td>Energy efficiency maximization</td>
<td>None</td>
</tr>
<tr>
<td>Transformability of input to output</td>
<td>None</td>
</tr>
<tr>
<td>Ideal function driven</td>
<td>Failure mode driven</td>
</tr>
<tr>
<td>Life cycle Cost &amp; Quality Loss driven</td>
<td>Warranty costs, Service costs</td>
</tr>
<tr>
<td>Upstream Technology reproducibility downstream</td>
<td>Design-Build-test-fix-test-fix HALT Calculator</td>
</tr>
</tbody>
</table>
Test Time Compression with HALT/HASS

Fatigue Failure S-N Curve

Onset of Failure for One Particular Failure Mode

Number of Cycles (N) Time or Cost
Highly Accelerated Life Test (HALT)

- Stresses product beyond specifications
- Gathers information on Product Limitations
- Focuses on Design Weakness & Failures
- 6 DoF Vibration
- High Thermal Rate of Change
- Loosely Defined - Modified “On the Fly”
- Not a “Pass/Fail” Test
Harmful Variation & Countermeasures

• Search for root cause & eliminate it
• Screen out defectives (scrap and rework)
• Feedback/feed forward control systems
• Tighten tolerances (control, noise, signal factors)
• Add a subsystem to balance the problem
• Calibration & adjustment
• Robust design (Parameter design & RSM)
• Change the concept to better one
• Turn off or turn down the power
• Correct design mistakes (putting diodes in backwards)
## Sales Points for Robust design

<table>
<thead>
<tr>
<th>Enabled</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible technology</td>
<td>to avoid having to reoptimize or reinvent a new design each time</td>
</tr>
<tr>
<td>Fewer experiments</td>
<td>to obtain required information.</td>
</tr>
<tr>
<td>Improved reproducibility</td>
<td>of experiments and measurements</td>
</tr>
<tr>
<td>Improved energy efficiency</td>
<td>through dynamic S/N ratios &amp; adjustment factors</td>
</tr>
<tr>
<td>Experimental planning</td>
<td>to reduce ad hoc / trial &amp; error testing</td>
</tr>
<tr>
<td>Bringing Improvement objective</td>
<td>to experimentation rather than just characterization</td>
</tr>
<tr>
<td>Preventing non-robust designs</td>
<td>from going downstream creating lots of trouble</td>
</tr>
<tr>
<td>Smoother subsystem integration</td>
<td>With coarse and fine tuning factor identification</td>
</tr>
<tr>
<td>Enabled</td>
<td>Reasoning</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Early input to reliability planning</td>
<td>to reduce excessive testing time</td>
</tr>
<tr>
<td>Reduced design complexity</td>
<td>for simpler software, simpler compensation systems, &amp; reduced information content</td>
</tr>
<tr>
<td>Identification of good tuning factors</td>
<td>for when process drifts or when system designer does subsystem integration</td>
</tr>
<tr>
<td>Capturing design engineering knowledge</td>
<td>for rapid product variants and future platform of products</td>
</tr>
<tr>
<td>Rapid maturation</td>
<td>of critical parameters and supporting critical specifications</td>
</tr>
<tr>
<td>Early identification</td>
<td>of technology limitations</td>
</tr>
<tr>
<td>Inspection of engineering knowledge</td>
<td>to prevent downstream problems</td>
</tr>
<tr>
<td>Identification of good measures</td>
<td>To enable consistently correct decisions</td>
</tr>
</tbody>
</table>
In reliability engineering, for example, Y is the continuous stochastic variable (time-to-failure) and F(x) is the failure mechanism, or mechanistic model. In RD, smooth transformability between input and output is considered.
Reliability Growth

Historically, the reliability growth process has been treated as a reactive approach to growing reliability based on failures “discovered” and fixed during testing or, most unfortunately, once a system/product has been delivered to a customer. This reactive approach ignores opportunities to grow reliability during the earliest design phases of a system or product.
Robustness Growth

Factors Can be changed today

Factors Can be changed in 1 week

Factors Can be changed in 2 weeks
Progression of Robustness to Ideal Function Development

When a product’s performance deviates from target, its quality is considered inferior. Such deviations in performance cause losses to the user of the product, and in varying degrees to the rest of society.
Main Function \( Y = f(x) + \varepsilon \)

Input signals \( M_i \)

Noise Factors

Control Factors

Useful Output

Harmful Output

Taxonomy of Design Function -- P Diagram
Spring Example
Simple Helical Spring Design

Main Function
\[ F = -kX + e \]

Useful Output

Input signal
\[ X \]

Zero Point Proportional Ideal Function

\[ Y = \beta M + \varepsilon \]

Force N

Ideal (Hooke’s Law)

Actual

Displacement X (mm)
Minimizing the effects of noise factors on transformation of input to output improves reliability. Sensitivity increase can be used for power reduction. Noise factor here might be fatigue cycles, or stress in one or two directions, or ...
# Typical Failure Modes and Causes for Mechanical Springs

<table>
<thead>
<tr>
<th>TYPE OF SPRING/STRESS CONDITION</th>
<th>FAILURE MODES</th>
<th>FAILURE CAUSES</th>
</tr>
</thead>
</table>
| Static (constant deflection or constant load) | - Load loss  
- Creep  
- Compression Set  
- Yielding  
- Fracture  
- Damaged spring end  
- Fatigue failure  
- Buckling  
- Surging  
- Complex stress change as a function of time | - Corrosive atmosphere  
- Hydrogen embrittlement  
- Parameter change  
- Cyclic (10,000 cycles or more during the life of the spring) | - Surface defects  
- Excessive stress range of reverse stress  
- Resonance surging  
- Misalignment  
- Excessive stress range of reverse stress **  
- Cycling temperature ... |
Analysis of Variance ANOVA

Resolution of the quantity of work which various types of sources have performed on the target characteristic. All factors affect variation. (screening?)

In physics, the quantity of work is proportional to the product of a generalized force and a generalized displacement.

Energy is always the product of a pair of variables e.g. Force and distance for mechanical, voltage and charge, pressure and volume, absolute temperature and $\Delta S$, magnetic potential and magnetic flux, chemical potential and quantity of material, moment and angular rotation, etc.

RD’s focus is on elements of energy transfer
Comparison experiment between two helical spring suppliers $A_1$ and $A_2$. Two replicates are measured for each supplier. Calculate S/N ratio for each supplier’s springs.

<table>
<thead>
<tr>
<th>Signal factor</th>
<th>$M_1=30$</th>
<th>$M_2=60$</th>
<th>$M_3=90$</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$</td>
<td>65N</td>
<td>136</td>
<td>208</td>
<td>$A_1$</td>
</tr>
<tr>
<td>$R_2$</td>
<td>74</td>
<td>147</td>
<td>197</td>
<td>$A_1$</td>
</tr>
<tr>
<td>Total</td>
<td>139</td>
<td>283</td>
<td>405</td>
<td></td>
</tr>
</tbody>
</table>

| $R_1$         | 61       | 135      | 201      | $A_2$    |
| $R_2$         | 71       | 145      | 208      | $A_2$    |
| Total         | 132      | 280      | 409      |          |
Robustness S/N ratio ANOVA Calculation

\[ S_T = y_{11}^2 + y_{11}^2 + \ldots + y_{kr_0}^2 \]
\[ df = kr_0 \]
\[ E(S_\beta) = r_0 r \beta^2 + \sigma^2 \]
\[ r = M_1^2 + M_2^2 + \ldots + M_k^2 \]
\[ S_\beta = \frac{1}{r_0 r^0} \left( M_1 y_1 + M_2 y_2 + \ldots + M_k y_k \right)^2 \]
\[ df = 1 \]
\[ S_e = S_T - S_\beta \]
\[ df = kr_0 - 1 \]
\[ V_e = \frac{S_e}{kr_0 - 1} \]
\[ \eta = 10 \log_{10} \frac{1}{r_0 r} \left( S_\beta - V_e \right) \]

Power of signal to change useful output

Power of Noise to change harmful output

Total Sum of Squares

Total Degrees of freedom

Expected value of \( \beta \)

Power of signal

Sum of squares for slope \( \beta \)

Degrees of freedom for \( \beta \)

Sum of squares for error

Degrees of freedom for error

Error Variance
S/N Ratio Calculation & Comparison for Two Suppliers $A_1$ & $A_2$

$S_T = 65^2 + 74^2 + \ldots + 197^2 = 131879$

$df = 6$

$r_0r = 2 \times (30^2 + 60^2 + 90^2) = 25,200$

$S_\beta = \frac{(M_1y_1 + M_1y_1 + M_1y_1)^2}{r_0r} = \frac{(30 \times 139 + 60 \times 283 + 90 \times 405)^2}{25200} = 131657.14$

$df = 1$

$S_e = S_T - S_\beta = 131879 - 131657.14 = 221.86$

$df = 5$

$V_e = \frac{S_e}{5} = \frac{221.86}{5} = 44.37$

$\eta_{A_1} = 10 \log \frac{1}{25200} \frac{(131657.14 - 44.37)}{44.37} = 10 \log .1177 = -9.29 \text{dB}$

$\eta_{A_2} = -7.79 \text{dB}$

Supplier $A_2$ better by 1.5 dB
Main function is to transform input signal to useful output. Energy transformation takes many different forms, (but usually not 2\text{nd} order polynomials, as in RSM)

**Common Ideal Function Forms:**

\[ Y = M + \varepsilon \]
\[ Y = \beta M + \varepsilon \]
\[ Y - Y_0 = \beta (M - M_0) + \varepsilon \]
\[ Y = \alpha + \beta M + \varepsilon \]
\[ Y = \beta M_1 M_2 + \varepsilon \]
\[ Y = \beta \frac{M_1}{M_2} + \varepsilon \]
\[ Y = \left| \bar{\beta} + \beta^* \left( M^* - \bar{M}^* \right) \right| M + \varepsilon \]
\[ Y = 1 - e^{-\beta M} + \varepsilon \]
\[ Y = \beta M^x + \varepsilon \]
\[ Y \bar{Y} = (R + jX)(R - jX) + \varepsilon \]
\[ Y = \alpha + \beta (M - \bar{M}) + \varepsilon \]
\[ \ldots \]
Measurements Discussion
Measurements

- One of the most important distinctions between robust design (RD) activities and reliability engineering (RE) is what is being measured during experimentation. Time-to-failure (TTF), typically used in reliability testing, is a continuous stochastic variable with an associated probability distribution, e.g., Weibull, normal, lognormal, ...

Rarely has TTF been used for robust design, other than for isolated verification testing. RD focus is on smooth energy transformation of input to output...
Typical Reliability Measures

- Life data
- Time-to-failure
- Time between failures
- Survival Count
- Event times
- Degradation of performance (of items below)

Typical Robust Design Measures

- Force, Current
- Pressure Voltage
- Velocity Intensity
- Temperature RPM
- Weight Angular velocity
- Distance Magnetic potential
- Thickness Time relative to ideal
- Torque Luminous Flux
- Volume ...
- Flow rate
RD Criteria for Measurement

- Validity first
- Continuous variable (richest analytics)
- Completeness
- Fundamental, disaggregated
- Practical, affordable
- Monotonic with control factors
- Related to basic energy transfer mechanism
- Measurement Capability High
- Engineering Focus
- Picks up information about dysfunction
- Open loop

Try not to measure ‘ideally zero‘ quantities
Lack of monotonicity of ‘misregistration’ measurement

Four paper stacks with same $\Delta X$. Same number indicates different problems and different required countermeasures. Yield?
Science & Engineering Attitude

• In science, understanding nature, searching for an accurate relational equation, and uncovering patterns and symmetries are most important. Reduction of error between observed characteristic value and the relational equation prediction is paramount. This method is completely correct as a scientific objective, i.e. searching for a formula which correctly expresses observational data.

• Engineering attitude however must consider profitability, excellence, efficiency of R&D. Low cost competitive designs which can operate with small variation even when subjected to combinations of worst predicted customer usage conditions, manufacturing tolerances, and degradation processes are required.

RD is more engineering oriented while Reliability (POF) is more science oriented!
Marginal Means Plot from L₉ Experiment Data

4 Factors @ 3 levels

Combination A₂B₂C₂D₂ ~ Mean
A₃B₁C₃D₃ = max response
A₁B₃C₁D₁ = min response
Error % ~20%

Response or Sensitivity or S/N ratio
Ideal Function Examples
Automotive Brake Pad Example

Ideal Y vs. M

Reality Y vs. M

M = Master cylinder Pressure

Y = Torque Generated

Adjustment signal M* = Pad surface area

Y = torque generated

Ideal Function = Y = $\beta MM^*$
Braking Ideal Function: \( Y = \beta MM^* \)

- \( M^* \): Pad surface area
- \( M \): Master cylinder pressure

Control factors:
- Raw Materials
- Raw material prep process parameters
- Pad manufacturing process parameters
- Dimensions, ...

Symptoms / side effects:
- Brake Noise
- Part Breakage
- Wear
- Vibration,
  - squealing ... GM Working on this one for many years!

Noise factors:
- Temperature/humidity variability
- Deterioration and aging
- Brake fluid type and amount
- Manufacturing variability
- Raw materials lot-to-lot & within lot
- Variability in process parameter settings
Numerical Control Machine (NC)

Ideal Function: Transform programmed dimensions into product dimensions

A generic test piece rather than an actual part, can be designed. The test piece can be easier to measure accurately. It also can evaluate multiple levels of signal factor.

Control Factors: Speed, Feed rate, Tool Material, Tool travel, Tool stiffness, cut Depth, tool angle, ...

Noise Factors: Material Hardness, tool wear, Lubricant age, Lubricant condition, ...

Lots of dimensions to measure by CMM~67 level signal factor
Generic test piece  Transformability

Ideal Function
\[ Y = M + e \]

Hardness 1
Hardness 2

Part Dimensions

NC machine Intended dimension (mm)
Measurement System Ideal Function
\[ Y = \beta M + e \]
M=true value of measurand
Y=measured value

Auto Steering Ideal function
\[ Y = \beta M + e \]
M=steering wheel angle
Y=Turning radius

Communication system ideal function
\[ Y = M + e \]
M=signal sent
Y=signal received

Cantilever beam Ideal Function
\[ Y = \beta \frac{M}{M^*} + e \]
M=Load
M*=Cross sectional area

Fuel Pump Ideal Function
\[ Y = \beta M \]
Y=Fuel volumetric flow rate
M=I/V/P current, voltage, & backpressure
Laser welding for Lap Joint Ideal Function
\[ Y = \beta M M^* + e \]
M = displacement
M* = Length
Y = measured shear force

Windshield wiper Ideal Function
\[ Y = \beta M + e \]
Y = measured arrival time for wiper to reach a fixed point
M = Theoretical, ideal time for which system was designed \(1/\text{rpm}\) of the motor

Metal Stamping ideal function
\[ Y = \beta M + e \]
Y = thickness change \((t_0 - t)\) after stamping
M = intended height change
Minimize \(\beta\)
**Adhesive film** ideal function

\[ Y = \beta M + e \]

\( Y \) = peel strength

\( M \) = contact width

Maximize \( \beta \)

**Roll Mill** ideal function

\[ Y = \beta M + e \]

\( Y \) = Thickness change

\( M \) = reduction ratio

Maximize \( \beta \)

Determine the limiting value for thinness.

More robust condition would enable thinner
POF
POF Underpinnings

Knowledge of how things fail and the root causes of failures enables engineers to identify and avoid unknowingly creating inherent potential failure mechanisms in new product designs and solve problems faster.

“Knowing how & why things fail is equally important to understand how & why things work”

POF is applicable to the entire product life cycle.
Physics of Failure and FEA

Where do the stresses exceed the strength of the materials?

Finite Element Analysis (FEA) is a traditional engineering technique for predicting the responses of structures and materials to applied loads such as force, temperature, vibration and displacements. NASTRAN, ABACUS, ...
RSM
Response Surface Methods (RSM)
Plateaus & Some Robustness

Requires construction of a mathematical model via response surface methods (RSM). Typical model is a second order polynomial model of the form:

\[ Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2 + \epsilon \]

The model approximates the unknown true response function by the first few terms of a Taylor’s series expansion. RSM has recently been enhanced by inclusion of Propagation of error (POE) methodology.

\( \beta \)'s are unknown coefficients to be estimated from experimental data. \( \epsilon \) is an unknown calculable error.
Propagation of Error & RSM

Variation from factor A setting is transmitted to variation in response Y. How much variation depends on nonlinearity of relationship and input variation.

\[ \sigma_Y^2 = \sum_{i=1}^{k} \left( \frac{\partial y}{\partial x_i} \right)^2 \sigma_{x_i}^2 + \sigma_{\text{resid}}^2 \]

\[ Y = \beta_0 + \beta_1 A_1 + \beta_{11} A_1^2 \]

\[ \hat{Y} = 15 + 25 A_1 - .7 A_1^2 \]

\[ \frac{\partial y}{\partial A} = 25 - 1.4 A \]

\[ \sigma_Y = \sqrt{(25 - 1.4 A_1)^2 \sigma_A^2 + \sigma_{\text{resid}}^2} \]
Central Composite Design

RSM Graphics
<table>
<thead>
<tr>
<th>Robust Design</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus on design transfer functions, ideal functions</td>
<td>Focus on design dysfunction, failure modes, failure times, mechanisms of failure</td>
</tr>
<tr>
<td>Engineering focus, empirical models, Generic Models, statistics</td>
<td>Mechanistic understanding, science oriented approach,</td>
</tr>
<tr>
<td>Optimization of functions with verification testing requirement</td>
<td>Characterization of natural phenomena with root cause analysis and countermeasures</td>
</tr>
<tr>
<td>Orthogonal array testing, Design of Experiments planning</td>
<td>Life tests, accelerated life tests, highly accelerated tests, accelerated degradation tests, survival</td>
</tr>
<tr>
<td>Multitude of Control, noise, and signal factor combinations for reducing sensitivity to noise and amplifying sensitivity to signal</td>
<td>Single factor testing, some multifactor testing. Fixed design with noise factors, acceleration factors</td>
</tr>
<tr>
<td>Actively change design parameters to improve insensitivity to noise factors, and sensitivity to signal factors</td>
<td>Design-Build-test-fix cycles for reliability growth</td>
</tr>
<tr>
<td>Robust Design</td>
<td>Reliability</td>
</tr>
<tr>
<td>------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Failure inspection only with verification testing of improved functions</td>
<td>Design out failure mechanisms. Reduce variation in product strength. Reduce the effect of usage/environment.</td>
</tr>
<tr>
<td>Synergy with axiomatic design methodology including ideal design, and simpler design</td>
<td>Simplify design complexity for reliability improvement. Reuse reliable hardware</td>
</tr>
<tr>
<td>Hierarchy of limits including functional limit, spec limit, control limit, adjustment limits</td>
<td>Identify &amp; Increase design margins, HALT &amp; HASS testing to flesh out design weaknesses. Temperature &amp; vibration stressors predominate</td>
</tr>
<tr>
<td>Measurement system and response selection paramount</td>
<td>Time-to-failure quantitative measurements supported by analytic methods</td>
</tr>
<tr>
<td>Ideal function development for energy relate measures</td>
<td>Fitting distributions to stochastic failure time data</td>
</tr>
<tr>
<td>Compound noise factors largest stress. Reduce variability to noise factors by interaction between noise and control factors, signal and noise factor.</td>
<td>HALT &amp; HASS highly accelerated testing to reveal design vulnerabilities and expand margins. Root cause exploration and mitigation</td>
</tr>
</tbody>
</table>
Summary

- RD methods and Reliability methods both have functionality at their core. RD methods attempt to optimize the designs toward ideal function, diverting energy from creating problems and dysfunction. Reliability methods attempt to minimize dysfunction through mechanistic understanding and mitigation of the root causes for problems.

- RD methods actively change design parameters to efficiently and cost effectively explore viable design space. Reliability methods subject the designs to stresses, accelerating stresses, and even highly accelerated stresses, [to improve time and cost of testing]. First principle physical models are considered where available to predict stability.

- Both RE and RD methods have strong merits, and learning when and how to apply each is a great advantage to product engineering teams.
Thanks for you kind attention 😊

• Presentation .PDF will be available shortly on www.opsalacarte.com

• Send comments and questions to Loul@opsalacarte.com
APPENDIX
Upcoming Reliability Webinars

Our next FREE Webinar will be on: June 6, 2012
Which topic would you like to see?
1. Choosing the right Accelerated Life Test
2. Getting the most out of your FMEA
3. ROI for Design for Reliability
4. ROI for HALT Calculator

Send answer to:  mikes@opsalacarte.com