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AXIOMATIC DESIGN QUALITY ENGINEERING - A TRANSMISSION PLANETARY CASE STUDY

Basem El-Haik, Ph.D.
Textron Inc.

James M. Wasiloff
DaimlerChrysler Corporation

ABSTRACT

Keywords: Axiomatic Design, Robust Design, Six Sigma, Design For Six Sigma, Quality Engineering

The objective of this paper is to present a simple and comprehensive integrated Design for Six Sigma (DFSS) approach to design robustness. The approach is hinged on conceptual components for axiomatic design, robust design and Six Sigma. An automatic transmission planetary case study is provided as an illustration vehicle. Specifically, this paper will explore the cascading process of functional requirements to design parameters and features while providing an initial robustness assessment against the common sources of variation. A Six Sigma design quality level is pursued as an objective. The approach presented in this paper represents a stream of development to achieve excellence by improving customer satisfaction through quality enhancement efforts. It can be viewed as a process with detailed steps needed to cast a complete understanding of how to achieve desired breakthrough design improvement. The method presented here relies heavily on the DFSS theory developed by Yang and El-Haik (2003).

1 INTRODUCTION

The DFSS method presented here has three components, Axiomatic Design, Robust Design and Six Sigma. Axiomatic Design zigzagging methods were employed to cascade requirements from the highest level House of Quality to system, sub-system and component levels. Design axioms were utilized within the cascading process to manage design coupling. Coupling is defined as the lack of or absence of design controllability in setting parameters that generate a design solution without conflicting requirements. Robust Design concepts of the P-Diagram, Noise and Control strategies and Ideal Function were used to obtain robustness at the Six Sigma level. Robustness is defined as the ability to provide design functional requirements that are insensitive to sources of variation. Sigma levels are the measure of robustness adopted in this study.

This paper begins with a discussion of the DFSS background (Section 2) followed by a review of Axiomatic Design (Section 3), Robust Design (Section 4), the two major components of the DFSS method presented here. A discussion of the DFSS integrated approach is presented in Section 5. A real world application is illustrated in Section 6. Conclusions are presented in Section 7.

2 BACKGROUND

The effect of the design methods on product design and its manufacturing is very profound. Not only design methods dictate different materials and processes but also the adoption of the product in prospective releases. The growth or the continuous use of the product can be predicted and future design alterations can be easily introduced when the design practices follow pre-specified design rules, especially those promoted to axioms. Design axioms do not substitute any other knowledge. Nor do axioms replace the need to constantly learn, adopt and implement new knowledge in the related disciplines. Deployment of design axioms complements the specific knowledge needed to develop healthy products.

This paper presents a new approach to the design of a vehicle automatic transmission planetary that heavily relies on design axioms, robust design, and Six Sigma methodologies. The axiomatic design approach deployed in this paper is a requirements cascading method. The integration of the axiomatic approach with the robustness approach provides new and useful perspectives of the design in hand. Together with Six Sigma allow more utilization of resources, provide flexibility to design changes, and highlights areas where improvements can be introduced.

The application presented here was a pilot for the presented integrated method and have been considered a successful case study by management and engineers. The paper balances between the technical findings and the tool integration.

3 AXIOMATIC DESIGN

Motivated by the absence of scientific design principles, Suh (1990) proposed the use of axioms as the scientific foundations of design. Out of the twelve axioms first suggested, Suh introduced the following two basic axioms along with six corollaries that a design needs to satisfy :

Axiom 1: **The Independence Axiom**
Maintain the independence of the functional requirements

Axiom 2: **The Information Axiom**
Minimize the information content in a design

In axiomatic design approach, the engineering design process is described in Figure 1, in which the array of functional requirements *(FRs)* is the minimum set of independent requirements that completely characterizes the design objective based on customer attributes (*CAs*). Design is defined as the creation of synthesized solution to satisfy perceived needs through the mapping between the *FRs* in the functional domain and the design parameters (*DPs*) in the physical domain and through the mapping between the *DPs* and the process variables (*PVs*) in the process domain.

The physical and process mappings can be expressed mathematically as

$$\{FR\}_{mx1} = [A]_{mxr}\{DP\}_{rxr1} \qquad (1)$$

$$\{DP\}_{rx1} = [B]_{rxn}\{PV\}_{nx1}$$

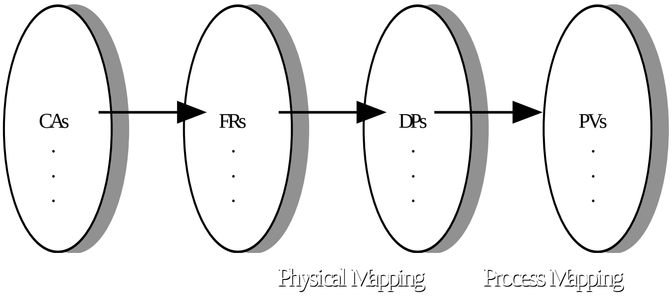

Figure 1. The design process mappings

where $\{FR\}_{mx1}$ is the vector of independent functional requirements with *m* components, $\{DP\}_{rx1}$ is the vector of design parameters with *r* components, $\{PV\}_{nx1}$ is the vector of process variables with *n* components, ***A*** is the physical design matrix, and ***B*** is the process design matrix. The mapping process can be mathematically abstracted as the following matrix equation: $\{FR\} = [A]\{DP\}$, where ***FR*** is the array of *FRs*, ***DP*** is the array of *DPs*, and ***A*** is the design matrix that contains the sensitivity coefficients of the *FRs* to the mapped-to *DPs*. The process mapping is described by: $\{DP\} = [B]\{PV\}$ The subsequent development uses the physical mapping for illustration purposes. Nevertheless, the results and conclusions are equally applicable to the process mapping as well.

After satisfying the Axiom 1, design simplicity is pursued by minimizing the information contents per Axiom 2, where the information content is defined as a measure of complexity. Maesures of design complexity can found in (El-Haik & Yang, 1999).

3.1 The Implications of Axiom 1

Axiom 1 states, that, the design parameters (*DPs)* and the functional requirements (*FRs)* are related such that a specific *DP* can be adjusted to satisfy its corresponding *FR* without affecting the other functional requirements, which will require that ***A*** should be either a diagonal matrix or triangular matrix. An element A_{ij} in ***A*** is a sensitivity coefficient of the functional requirement FR_i with respect to the design parameter DP_j, i.e., $A_{ij} = \partial FR_i / \partial DP_j$. The shape and dimension of matrix ***A*** is used to classify the design as *uncoupled*, *decoupled*, *coupled*, or *redundant*. In the first three categories, the number of functional requirements, *m*, is greater than or equals to the number of design parameters, *p*. In a redundant design, we have $m < p$. A design that complies with the independence axiom is called an *uncoupled design*. The design matrix, ***A***, is a square ($m = p$) diagonal matrix ($A_{ij} \neq 0$ when $i=j$ and 0 elsewhere) as in Eq.(3). An uncoupled design is ideal with many attractive attributes. First, it is a coupling-free design; the multiple optimization objectives of reducing functional variability and adjustment to target (sensitivity) can be achieved through only one design parameter, its respective *DP*. Second, the overall design complexity is apparently additive and can be reduced through optimizing the complexity of the individual *DPs*, separately. Third, cost and other constraints are more manageable and can be met more easily.

A violation of Axiom 1 occurs when two or more *FRs* are mapped to a common *DP*. A design that violates Axiom 1 can be either a decoupled (Eq.(4)) or a coupled design (Eq.(5)). The decoupled design matrix ***A*** is a square triangular (lower or upper) matrix. In extreme situations, ***A*** could be a complete or sparse matrix. In the complete case, we have the maximum number of non-zero entries (sensitivity coefficients), $p(p-1)/2$ where $A_{ij} \neq 0$ for $j=1,i$ and $i=1,p.$ A rectangular design matrix ($m>p$) represents a coupled design. Since a square matrix is a necessary, but not sufficient, requirement for independence, a coupled design may be changed to an uncoupled or decoupled design by adding *m-p* extra *DPs*, resulting in a dimensional increase of ***A***.

$$\begin{Bmatrix} FR_1\\ .\\ .\\ FR_m\end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & . & 0\\ 0 & A_{22} & 0 & .\\ . & . & . & 0\\ 0 & 0 & . & A_{mm}\end{bmatrix}\begin{Bmatrix} DP_1\\ .\\ .\\ DP_m\end{Bmatrix}$$

(Ucoupled Design)

(3)

$$\begin{Bmatrix} FR_1\\ .\\ .\\ FR_m\end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & . & 0\\ A_{21} & A_{22} & 0 & .\\ . & . & . & 0\\ A_{m1} & A_{m2} & . & A_{mm}\end{bmatrix}\begin{Bmatrix} DP_1\\ .\\ .\\ DP_m\end{Bmatrix}$$

(Decoupled Design)

(4)

$$\begin{Bmatrix} FR_1\\ .\\ .\\ FR_m\end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & . & A_{1p}\\ A_{21} & A_{22} & & .\\ . & & . & A_{(m-1)p}\\ A_{m1} & . & A_{m(p-1)} & A_{mp}\end{bmatrix}\begin{Bmatrix} DP_1\\ .\\ .\\ DP_p\end{Bmatrix}$$

(Coupled Design)

(5)

An example of design categories is presented in Figure 2 which displays two possible arrangements of the generic water faucet[1]. The uncoupled architecture will have higher reliability and more customer satisfaction since the multiple adjustment of the two *FRs* can be done independently to fit customer demands.

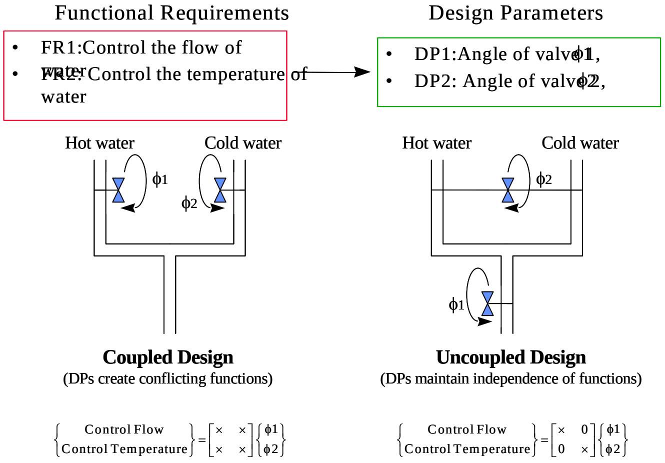

Figure 2: Example of Design Coupling

The design categories have twofold importance: first, they provide a sort of a design classification scheme and, second, they strengthen the need to assess the degree of coupling in a given design entity. Rinderle (1982), Suh and Rinderle (1982) proposed the simultaneous use of *Reangualrity*, *R*, and *Semangularity*, *S*, as coupling measures.

3.2 Requirements Cascading: The Zigzagging Approach

In the faucet example, the design is considered complete when the mapping from the functional domain to the physical domain is accomplished. However, in many design assignments of higher complexity, such as the vane pump, a process of cascading the high level conceptual requirements is needed. The objective of this process is decompose both the *FRs* and the *DPs* for further detailing before manufacturing implementation (see Figure xxx). The process should be detailed such that it will enable the mapping from *FRs* to *DPs* in a certain decomposition level and from the *DPs* to the *FRs* of a further detailed level. The *zigzagging process* of axiomatic design does just that. This process requires the decomposition in a solution neutral environment, where the *DPs* are chosen after the *FRs* are defined and not vice versa. When the *FRs* are defined, we have to *zig* to the physical domain, and after proper *DPs* selection, we have to *zag* to the functional domain for further decomposition. This process is in contrast with the traditional the cascading processes which utilize only one domain, treating the design as the sum of functions or the sum of parts.

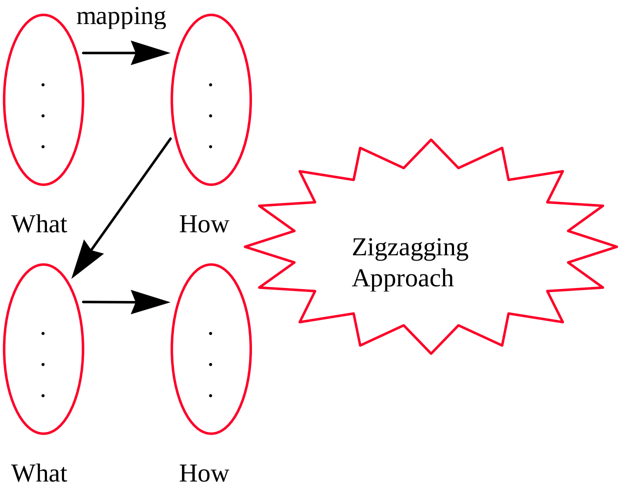

Figure 3: The Zigzagging Process

The process of zigzagging must continue until no decomposition can be done. This is warranted when a material properties or geometrical dimensions are reached, for example. Theoretically, the process can proceed to the physical and chemical structure of the design material precision of the design requires such actions. The results of the this process is the creation of the hierarchical tree for the *FRs* and the *DPs*.

4 ROBUST DESIGN

In the context of this research, the terms 'quality' and 'robustness' are used interchangeably. Robustness is defined as reducing the variation of the functional requirements of the system and having them on target as defined by the customer (Taguchi, 1986), (Taguchi and Wu, 1986), and (Taguchi et al., 1989). The operational weaknesses have been the subject of robust design (Taguchi, 1986) and control theory through methods such as parameter design, tolerance design and time domain stability and controllability theories. On the other hand, the conceptual weaknesses have been ignored due to the lack of methods, tools and processes that characterize, evaluate and solve them. While such a need can be identified, the real advantage is in having such processes integrated with the methods attacking the operational weaknesses. Therefore, quality methods and procedures that are integrated with design activities and compatible with their goals are badly needed to address both types of weaknesses in a coherence way.

The principal idea of robust design is that statistical testing of a product should be carried out at the design stage, the off-line stage, in order to make the product *robust* against the effects of variation in the manufacturing and use environments (Taguchi, 1986), (Taguchi & Wu, 1986), and (Taguchi et al., 1989). Taguchi treats the design problem from the view of quality and cost.

Quality is measured by statistical variability such as standard deviation or mean square error. The main criterion is keeping the CTQ on a target value, while minimizing variability. Robustness means that a system performs its intended function under all operating conditions (different causes of variations) throughout its intended life. The undesirable and uncontrollable factors that cause the *CTQ* under consideration to deviate from target value are called noise factors. Noise factors adversely affect quality and their negligence can result in different optimized system. Eliminating noise factors may be expensive. Instead, we can try to reduce the effect of the noise factors.

Robust Design is a disciplined engineering process that seeks to find the best expression of a system design. "Best" is carefully defined to mean that the design is the lowest-cost solution to the product design specification, which is based on the customer needs. Dr. Taguchi has introduced a holistic approach to the traditional engineering tasks of minimizing cost and maximizing quality by including the quality of the product as one more dimension of cost. High-quality systems minimize these costs by performing consistently.

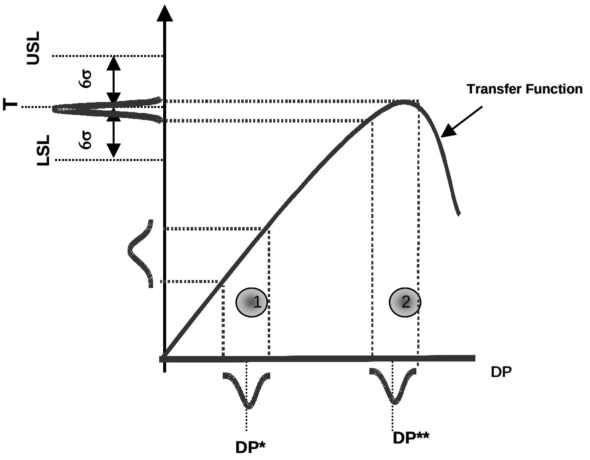

Figure 4 – Robust Design

Taguchi's philosophy of robust design is aimed at reducing the loss due to variation of performance from the target value based on the quality loss function, Signal-to-Noise (S/N) ratio, optimization and experimental design. *Quality Loss* is the loss experienced by customers and society is a function of how far performance deviates from target. The *Quality Loss Function (QLF)* relates quality to cost (Taguchi and Wu, 1986), (Taguchi, 1986) ,(Kacker, 1985). *QLF* is a better evaluation system than the traditional binary treatment of quality, i.e. within/outside specifications. (Kapur, 1988) illustrated the development of specification limits using quality loss function. The Quality Loss Function *(QLF)* is a quantitative description and has two components: deviation from on target performance and variability. The *QLF* can be approximated by a quadratic polynomial in the CTQ requirement. Figure 5 exhibits two scenarios where the loss on left scenario has lower loss than that of the right scenario, on the average, for the same performance level.

Taguchi draws a distinction between design parameters, or variables, over which designer has the control (input controls in the system sense) and noise variables. The idea of varying the design parameters as inputs to achieve target is not new. The important contribution is the systematic inclusion into experimental design of noise variables, that is, the variables over which the designer has no or little control. A distinction is also made between internal noise, such as component wear and material variability, and external noise, which the designer cannot control (e.g., humidity, temperature).

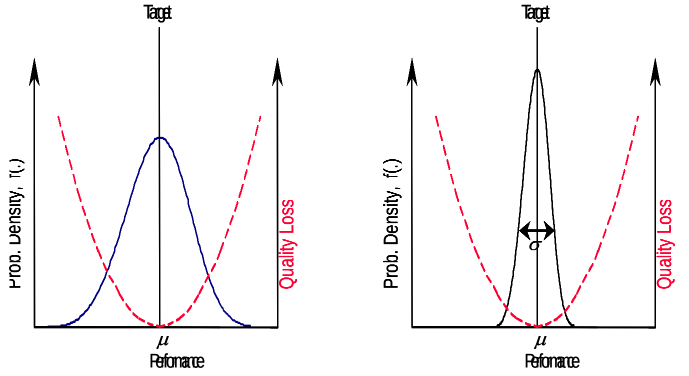

Figure 5: The Quality Loss Function

Robust design objective is to suppress, as far as possible, the effect of noise by exploring the levels of the factors that make the system insensitive to them. Robust design is concerned with the product/process *functional requirement* and methods to provide this function at lowest overall cost and targeted quality level under the variability produced by the noise factors. Consider two levels or means of a design parameter, level 1 and 2, having the same variance and distribution in Figure xxx. It is obvious that Level 2 produces less variation in the CTQ than level 1. Level 2 will also produce a lower quality loss similar to scenario on the right of

The noise factors affect the *FRs* or *CTQs* at different segment in the life cycle (see Figure xxx). As a result, they can cause dramatic reduction in product reliability. Early life failures can be attributed to manufacturing variability. The unit to unit noise causes failure in the field when the product is subjected to external noise. The random failure rate that characterizes most of the product life is attributed to external noise. Deterioration noise is active at the end of life. Therefore, a product is said to be robust (and reliable) when it is insensitive to the effect of noise factors, even though the sources themselves have not been eliminated (Creveling 1995).

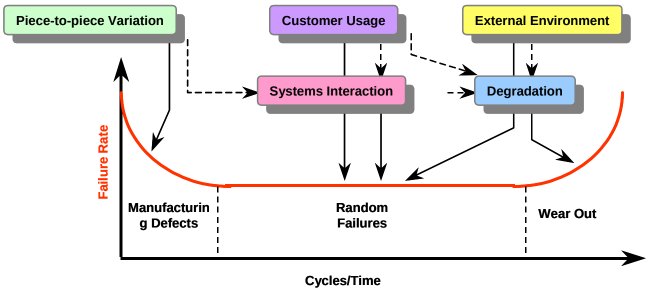

Figure 6 The Effect of Noise Factors During The System Life Cycle

5 DFSS APPROACH

The process adopted by companies that are exhibiting success in quality improvements vary. However, two major elements can be factored out: Customer satisfaction and continuous improvement are absolutely paramount.

Engineering and physics disciplines are the very foundation of a good conceptual design or fixing vulnerabilities (problems) with an existing system. The designers (both individual & teams) have used these disciplines for many generations. However, in today's' comprehensive way to design they are no longer enough. The trend now in automotive, and many other industries, requires a disciplined engineering process that ties together the multitude of the tools being taught and used. Axiomatic design serves this trend very well. It provides perspectives that usually overlooked by other methods. The need to pilot and deploy this process for linking the principles of quality engineering and product conceptualization inspired the initiation of this paper (Fowlkes & Creveling 1995).

Quality engineering is a disciplined approach that seeks to find the *best* expression of a product. That is, the lowest cost solution to the product specification, which is based on customer needs. Dr. G. Taguchi introduced quality as one more dimension to cost. High quality products when perform consistently will have lower life cycle cost. Quality engineering focuses on parameter optimization. these are done by reducing the variation of the key functional requirements (*FRs*) and ensuring that those *FRs* can be easily adjusted onto the nominal value. Minimizing variation or making the system less sensitive to variation make it possible to decrease cost, as expensive cost for controlling quality are no longer necessary (Fowlkes & Creveling 1995).

The causes of variation in the *FRs* are called *noise factors*. Noise factors are defined, in general, as any thing that causes an FR to deviate from its target value. There are 5 type of noise factors:

- Manufacturing variability (unit-to-unit noise) is a result of the inability to manufacture two parts exactly alike. Manufacturing processes and mach8nes are two major sources
- Customer usage noise. Customer exhibits different patterns of using a given product and hence different duty cycles are generated.
- Deterioration (internal) noise which represents product aging.
- Environment (external) noise which are sources of variability that comes outside of the product such as temperature and humidity.
- Coupling noise. This a system noise that happens because of the physical mapping decisions (see Section 2.1).

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The zigzagging process when coupled with quality engineering allows the identification of areas were further improvement can be sought. This in turn allows better use of the engineering and testing resources.

6 APPLICATION

An application involving an automobile automatic transmission, a highly coupled and complex electromechanical hydraulic kinematic system, was selected to illustrate key DFSS principles. A major sub-system, the planetary assembly, requires high mileage reliability and robustness as demonstrated through field history, life testing and laboratory fatigue testing. Planetary reliability is strongly correlated to the life of the engineered system defined as the interface between the pinion gear bore, needle bearing and pinion shaft. A planetary gear system is a highly efficient epicyclic kinetic mechanism with two degrees of freedom. A gear train with two degrees of freedom can be used to couple two inputs from into one output. For simple transmission of power from an input to and output, which occurs in an automobile automatic transmission, only one degree of freedom is needed. The planetary system is restricted to a single degree of freedom by simply locking individual components to ground. A primary compenent is designated the “pinion” (also known as a “planet”) gear because it is not fixed to the ground and is free to “orbit” the sun gear. A central gear, called the “sun gear” because it’s center is fixed to ground and it is being orbited by the planet gear. Unlike ordinary gear trains, the system is not grounded and frees up an inter-connecting arm to rotate. This arm is referred to as the “carrier”. The Pinion gear, turns on a shaft fixed in the carrier. The pinion gear is positioned radially on the shaft on a roller bearing and axially between thrust Washers. Finally, “ring” or “annulus” gear can be fixed to ground to eliminate one degree of freedom. By selectively grounding or ”holding” various elements of the planetary, speed reduction, speed reversal and a speed increase may be achieved, thus providing the key functional requirements of an automatic transmission.

Voice of the Customer was processed and translated into engineering terms and functional requirements as a result of a comprehensive automotive system Quality Function Deployment (QFD) House of Quality. A team of subject matter experts convened to collaborate on translation of customer attributes (CA’s) into functional requirements (FR’s) in preparation for requirement cascading process using the “Zigzagging” Axiomatic Design decomposition process. Reference Yang and El-Haik, 2003.

Functional Requirements of the Needle System:
FR1: Transmit Carrier Torque
FR2: Transmit Rotation
FR3: Create Radial Force
FR4: Locate Pinion Gear

Design Parameters of the Needle System:
DP1: Diametrical Clearance
DP2: Circumferential Clearance
DP3: Shaft Surface Characteristics
DP4: Pinion Bore Surface Characteristics

$$\begin{Bmatrix} FR_1 \\ FR_2 . \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} 0 & 0 & A_{13} . & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & 0 & 0 \\ A_{41} & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 . \\ DP_3 \\ DP_4 \end{Bmatrix}$$

(Coupled Design)

Requirement cascading was accomplished thru the zigzagging process from the customer level down to super-system, system, subsystem and component levels as depicted in Figure x. The plethora of component mapping and resulting design matrices as a result of the zigzagging process converged on one highly coupled component region. The results allow us to identify the “critical few” design parameters for subsequent optimization within this region. The following automatic transmission planetary gear system was decomposed:

- Annulus Gear
- Planetary Carrier
- Sun Gear
- Pinion Gear

The pinion gear needle bearing component is the subject of this case study and is shown in Figure (8).

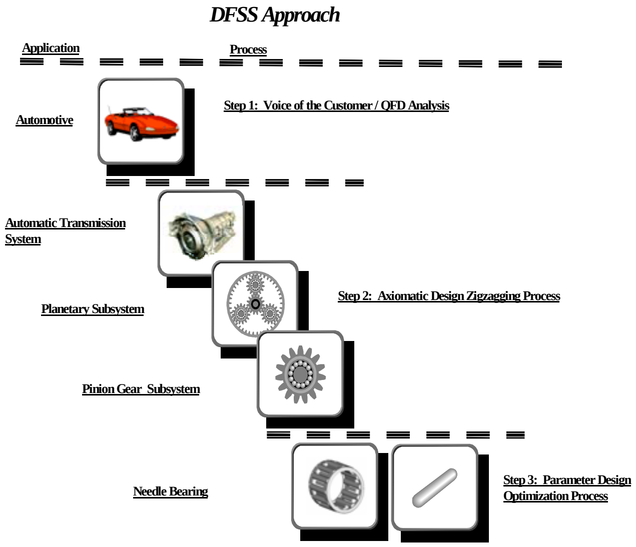

Figure 7: DFSS method

Figure 8: Planetary Design Matrix

A P-diagram was constructed to identify the ideal function, noise factors, control factors and the energy transformation concept as shown in Figure 9.

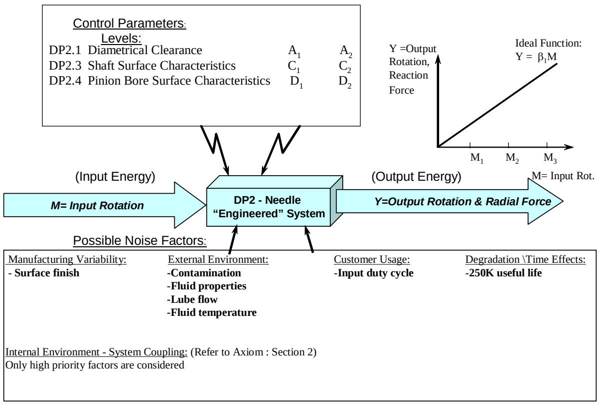

Figure 9: P – Diagram: Planetary Pinion Needle System

The compound noise strategy developed is shown in Figure 10.

Noise Factor	N1 "Good" Level	N2 "Bad" Level
Lubrication Flow	Improved Flow	Current Flow
Lubrication Properties	"New" oil	Aged oil
Degrade (Usage)	"New" rollers	"Aged" rollers

Figure 10: Compound Noise Strategy

The experiment control factors are identified in Figure 11.

Control Factor	Level 1	Level 2
DP2.1 Diametrical Clearance	**A1 - Current specification**	**A2 - Reduced Clearance**
DP2.3 Shaft Surface Characteristics	**C1 - Current specification**	**C2 - Improved Finish**
DP2.4 Pinion Bore Surface Characteristics	**D1 - Current specification**	**D2 – Three Stage Hone**

Figure 11: DOE Control Factors

The final experiment orthogonal array is depicted in Figure 12.

	Control Factors			Noise Factors					
	DC	Shaft OD	Gear ID	N1	N2	N1	N2	N1	N2
1	A1	C1	D1	120	105	135	110	150	125
2	A1	C2	D2	120	105	125	115	145	145
3	A2	C1	D2	120	102	135	118	155	208*
4	A2	C2	D1	135	100	125	112	155	140
5	A2	C2	D2	130	105	130	115	150	135
6	A2	C1	D1	130	110	135	122	145	150
7	A1	C2	D1	120	100	125	115	150	145
8	A1	C1	D2	120	105	130	120	140	170

Figure 12: Orthogonal Array

An example of a main effects plot of mean response at 9000 rpm is shown in figure 13.

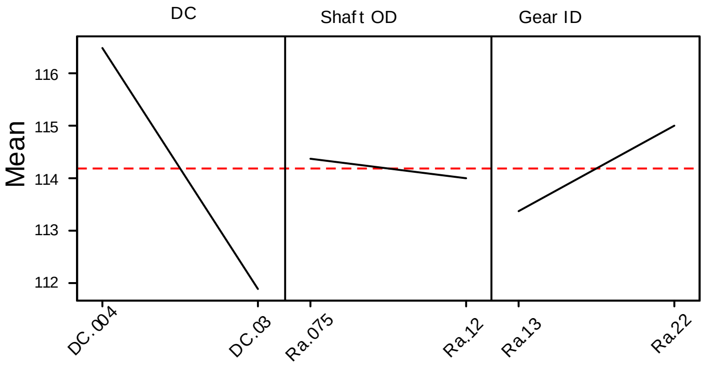

Figure 13: Main Effects Plot for Means

A sample main effect plot for signal to noise ratios is shown in figure 14.

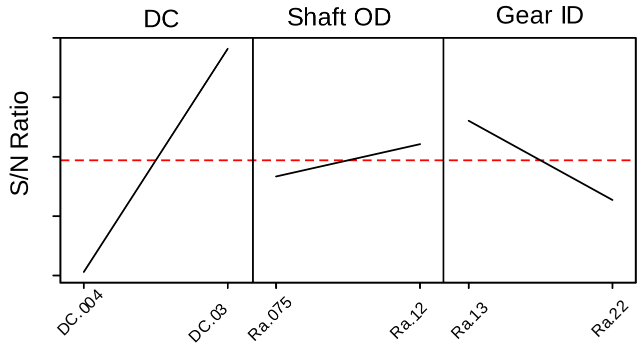

Figure 14: Main Effects Plot for S/N Ratios

Experiment Findings:

Overall, the predicted optimal design resulted in a signal to noise ratio of 16.5 which represented a 6 db improvement over the baseline design. Confirmation results indicated a signal to noise ratio of 16.1, a 5.6 db improvement over the baseline design. Subsequent life testing and Weibull probability plots confirmed a significant improvement in useful life and high mileage reliability. The design parameters under study have been proven to significantly effect life of the planetary system. Thru this application of DFSS, reliability and robustness of the planetary system were improved by 28% at 150,000 miles. An optimization model is now developed that can be applied to future design iterations and emerging products.

7 CONCLUSIONS

The DFSS methodologies described herein represent powerful tools in achieving high level quality and reliability goals. In particular, Axiomatic Design (design axioms, cascading process, design matrices, etc.), integrated with Robust Engineering principles was highly effective in translating customer based functional requirements into design parameters for optimization. The automatic transmission case study provides a practical, real world confirmation of the theory presented.

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