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Root Cause Analysis of Product Service Failure Using Computer Experimentation Technique

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Abstract

Improvement of product quality and reliability following field failures of products is a well-researched area. The feedback from the service in the form warranty / field performance is important in guiding design and manufacturing changes. Traditionally, efforts in this area have been limited to analysis of warranty data for evaluating warranty policies, estimating field reliability, predicting failures etc. Also some research has been done on performing corrective actions in manufacturing via process adjustments by linking warranty failures with manufacturing Key Control Characteristics (KCCs). However there is also need to develop the systematic approach of doing Root Cause Analysis (RCA) and Corrective Actions in design. This research proposes a novel methodology of performing RCA and CA in design by linking warranty failures with the product design parameters such as Geometric Dimensioning and Tolerance (GD&T). An analytical approach based on computer experimentation technique performs effective Root Cause Analysis (RCA) of product failures by linking warranty failure modes with the design parameters and identifies the analytical relationship between them. The method focuses on identifying root cause(s) to address in tolerance product design faults. Warranty failures modes are represented by Key Failure Characteristics (KFCs) and the geometrical design parameters are represented by Key Product Characteristics (KPCs). The proposed methodology establishes the analytical relationship between the KFCs and KPCs using variation mechanistic models to identify the dimensional variations which caused the failure. A case study on automotive ignition switch demonstrates the methodology.

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Keywords :Product service failures, Root Cause Analysis, GD& T, factorial design, Design of Experiments

1. Introduction

The quality, reliability and safety are important aspects of the product throughout the product lifecycle stages. The product failure during the service stage such as warranty claims and No-Fault-Found (NFF) Failures results in significant cost towards warranty and customer dissatisfaction [1]. The product failures reported as warranty claims fail to deliver the expected reliability during the service phase. Such service failures are due to non-conformance and unmapped interaction between design, manufacturing and service stage [2].Although OEMs conduct best reliability & maintainability practices during product development stage, the NFF phenomenon is one of the major challenges for them. The occurrence of warranty defect is due to non-conformance of Design Parameters (DP) and Process Variables (PV) during design and manufacturing stages respectively. The non-conformance of such parameters defines that tolerance band assigned to DPs and PVs include the potential region vulnerable to warranty defects [3].

To address such non-conformance type of warranty failures, manufacturers analyze the warranty data reported from the service and provide feedback to guide the design and manufacturing modifications. Traditionally efforts have been made to integrate the warranty information with the manufacturing measurements or process variables i.e. PVs [4] to identify such in-specs fault region and provide process

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adjustments [5]. Also heuristic based problem solving approach has been developed to perform the root cause analysis of such failures addressing product design [6]. However there is no systematic or analytical approach which links the warranty failure modes with the design parameters. To address this gap, this research proposes, as first crucial step, to develop an analytical model for mapping failure modes obtained from the service with the key geometrical characteristics i.e. (GD&T) of the product design to identify the root cause and develop the corrective action.

The proposed methodology can be utilized to (i) identify the critical-to-quality and critical-to-functionality dimensions in the product assembly; (ii) measure the KFCs from service failures and the KPCs from design input; and (iii) mitigate the risks and reduce the time to address the service failure.

2. Current State of the art

The current practices for performing RCA and problem solving are heuristics based. Ford Motor Company developed and documented (8 Discipline) 8D method as a team oriented problem solving approach. In order to help the manufacturing and engineering teams to detect, treat and reduce the defects found in-service products. Also different analytical tools and techniques such as Pareto charts, 5-Whys, and Cause and effect diagram are used to tackle the issues encountered during field failure. 8 D method being a team based approach; different cross functional teams use such analytical tools to define measure, analyze and solve the problem and determine the root cause of product/ process failure.

Table.1. Related research on problem solving approach in Design & Manufacturing domain

Domain / Approach	Manufacturing	Design
Heuristic based	- Process Failure Mode Effects Analysis (PFMEA) - Eight Disciplines Problem Solving (8D) - Early Problem Solving (EPS) - Fault Tree Analysis (FTA) - Ishikawa Diagram	- Design Failure Mode Effects Analysis (DFMEA) - Eight Disciplines Problem Solving (8D) - Early Problem Solving (EPS) - Fault Tree Analysis (FTA)
Analytical	- Fault Region Localization (FRL)[4] - Functional Process Adjustments (FPA)[5] - Stream of Variation(SOVA) [7]	*-Proposed Methodology* Root Cause Analysis Module (RCAM)

However there are limitations with such heuristic centered method. Since the method is: (i) iterative and based on hit and trial approach; (ii) cost encountered to address the problem is high; and (iii) good for problem troubleshoot, but do not help to identify the root cause and it is time consuming. Many researchers have been done an analysis of warranty data and RCA addressing (i) the manufacturing related issues and field reliability through various heuristic and analytical methods; (ii) the design related issues through heuristic based approach. But there is a scope to build an analytical approach linking service-design domains. Table 1 summarizes past works on problem solving approach and RCA and also highlights the contribution of current research to serve the gap.

3. Methodology

This section describes the systematic methodology to link the measured warranty failures modes with the engineering design parameters to identify the root cause of product failure.

3.1. System

The proposed methodology identifies the root cause of electro -mechanical product failure due to geometric design parameter such as GD&T to facilitate a reduction in NFF events. The purpose of identifying the root cause is to develop the corrective actions to reduce the observed warranty failure from recurring in existing products and prevent them in future designs. The corrective approach determines the engineering change in the form of GD & T for the existing design and the preventive approach updates the Design Guideline and DFMEA. Figure 1 presents the methodological framework of the proposed analytical approach. The framework shows the 4-steps involved : (i) warranty data analysis ;(ii) identifying key failure modes; (iii) root cause analysis using Variation Response Method (VRM); (iv) developing corrective and preventive actions. This is followed by a detailed discussion of problem formulation and the steps of the methodology.

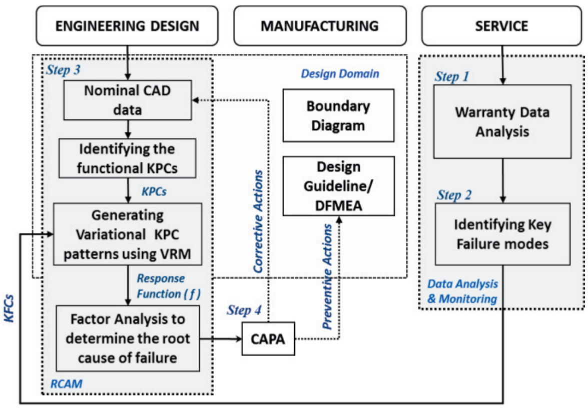

Figure.1. Proposed application framework for the Root Cause Analysis of Product Service Failure

3.2. Problem Formulation

To identify the root cause of failure in design parameters three main challenges have been identified: (i) identifying the Key Failure Characteristics (KFCs) which defines the failure modes obtained from the failed parts; (ii) identifying the functional Key Product Characteristics (KPCs) i.e. design parameters from nominal CAD data; and (iii) establishing the mapping function between the design parameters and the failure characteristics.

Key Failure Characteristics (KFCs): It represents all the key dimensional measurements and observations done on the failed samples from the field (warranty failures) which defines the failure characteristics of the parts or subassemblies.

Key Product Characteristics (KPCs): It represents all the key geometric design features identified from the nominal CAD data of the different body parts of a product assembly. Functional KPCs are the specific geometric features of different mating body parts which define the assembly and satisfy the functional requirements of the product. Identifying a set of functional KPCs is important to model the variational geometric features and the assembly constraints among such features.

Thus an integrated simulation framework needs to be developed- to determine the "response" function, i.e. 'f' to map the input variational geometrical features to the KFCs for the identified failure modes (see equation (1)).

$$KFCs = f(KPCs) \quad (1)$$

In order to identify the root cause of failure there is need to build a simulation model for performing sensitivity analysis and root cause identification. This can be stated from the equation (2) where 'g' is the inverse mapping function which translates product KFCs to control the variational KPCs.

$$\begin{cases} KPCs = g(KFCs) \\ g = f^{-1} \end{cases} \quad (2)$$

3.3. Approach

Step 1: Warranty Data Analysis

The reported service warranty failures can be classified as customer related, service related, manufacturing related or design related. Warranty data analysis is performed at first place to identify the critical warranty failures. Design related warranty failures can be attributed to the fact that target is incorrectly set during the design phase, especially GD & T. The product failure data is obtained from different service agents such as Customer Relationship Management (CRM) team, call centre, technical specialist report. Pareto Analysis is carried out based upon Warranty Claims Rate (WCR) to identify the failed components thereby detecting different failure modes. Such analysis will result in identifying components with low reliability; also it would identify dominant failure modes from in-service product failures. Further failure data can be classified into the groups to identify whether it is a manufacturing defect or the design error. If the dominant failure modes lie within the designed tolerance zone, such failures attribute to design related warranty failures. Thus root cause of such failures would be defined in the subdomain of Product Configuration or Design Parameter (DP).

Step 2: Identifying Key Failure Modes

A detailed analysis of the identified faulty components or subassemblies is carried out to understand the type of failure and its mechanism. To identify the key failure modes and understand the KFCs two step approach is followed: (i) Data monitoring step-wise; (ii) measurements/observations made step-wise. Data monitoring is performed in order to investigate the effects of several failure modes in a component or subassemblies. The failure mode frequency or relative failure frequency data identifies the critical failure modes which contribute to the in-service product failures. As an example, in case of particular automotive component failure say ten different failure modes were reported in the database through warranty claims, as listed in the Table 2. The defects count indicates the frequency data to determine the key failure modes which contribute to the product service failure.

Table.2. Failure Mode frequency data

Cumulative Percentage Cut-off: 80%			
Sr. No	**Causes**	**Defects Count**	**Cumulative (%)**
1	Failure Mode 1	650	28.4%
2	Failure Mode 2	570	53.4%
3	Failure Mode 3	420	71.7%
4	Failure Mode 4	225	81.6%
5	Failure Mode 5	130	87%
6	Failure Mode 6	75	91%
7	Failure Mode 7	70	94%
8	Failure Mode 8	59	96%
9	Failure Mode 9	48	98%
10	Failure Mode 10	39	100%

Based on Pareto Analysis as shown in Figure 2, top 9 modes account for 98% of total warranty claims. The most common failure modes are Failure Mode 1 up to Failure Mode 5, which cumulatively account for almost 87 % of the reported service failure. Relatively remaining failure modes have lower frequencies. In order to narrow down the approach and identify the root-cause the key failure modes are identified. In this case the identified set of key failure mode is {Failure Mode1, Failure Mode2,….., Failure Mode5}.

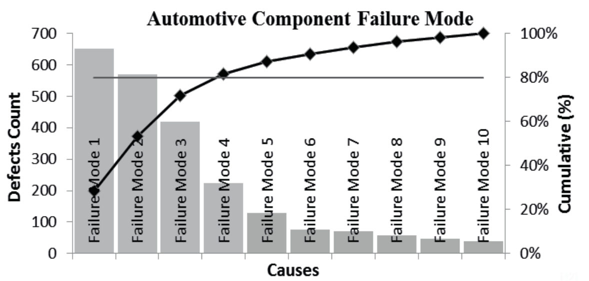

Figure.2. Pareto Analysis of Warranty Failure Modes

To quantify the failure data from different key failure modes KFCs are defined and are to be measured. The critical dimensions or GD & T is measured which characterize the key failure mode. A non-destructive technique like X-ray computed tomography can be used for performing the measurement.

Step 3: Root Cause Analysis Module (RCAM) using VRM

Firstly, Variation Response Method (VRM) simulation [8] is applied in this step to generate the response function to map the measured KFCs with the geometric design parameter for which variation must be controlled. Figure 3 shows the generic workflow of the RCAM with VRM implementation. VRM is a Mat-LAB based software architecture and is based on two main steps. In the first step, (i) geometric variational features are modelled accounting GD&T specifications; then (ii) assembly constraints are introduced among variational features to define the mating joints.

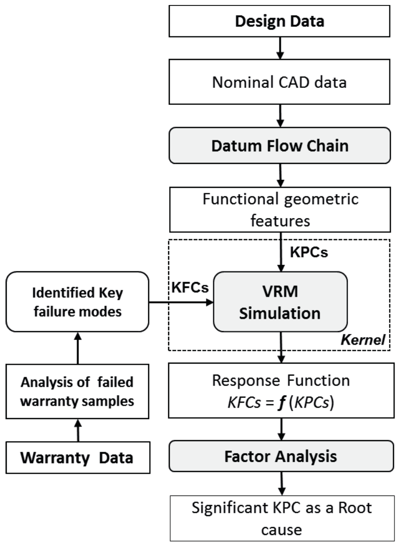

Figure.3. Workflow of Root Cause Analysis Module (RCAM)

Functional geometric features (KPCs) are the regions of the part which are important for assembly purpose and hence satisfy the functional requirements of the product. Customer Attribute (CA) defines the functional requirement of the product. A flow down tree chart approach is used to decompose the requirement into all the subassemblies and parts to identify the functional geometric features from the nominal CAD data of the product using Datum Flow Chain (DFC) technique [9]. The DFC relates the logic of datum to the parts or the subassemblies of the product in order to identify the mating features (KPCs) which define the functional characteristics of the product assembly. Initial configuration data is created for parametric modeling of the identified functional geometric features (KPCs) based on the nominal CAD data. This includes feature normal vector, geometric parameters, datum reference, and variational parameters. Variational parameters consists of dimensional tolerance and geometrical tolerance specifications. Dimensional tolerance accounts for the variation modelling of geometric parameters whereas geometrical tolerance accounts for the form or the position variation from the nominal CAD geometry. As the variational parameters have been defined, the assembly constrains are introduced among the mating geometrical features.

The above generated configuration data is fed as input to the VRM kernel. A detailed architecture of VRM can be found in [8]. As the rigid assemblies involve part to part variation, it is necessary to account for geometric variations of each individual part. Hence 4x4 homogeneous transformation matrices are embedded into VRM to completely define the location of the functional geometric features, with respect to the global coordinate system. For example, the homogeneous transformation matrix $\mathbf{T}_{0,\mathrm{j}}$ represents the transformation from frame $\mathbf{\Omega_j}$ to $\mathbf{\Omega_0}$ and can be expressed as 4x4 order. The **d** is the 3x1 position vector; **R** is 3x3 rotation matrix; $\mathbf{\Omega_0}$ is the global coordinate system; and $\mathbf{\Omega_j}$ is the local coordinate frame of the feature.

$$\mathbf{T}_{0,\mathrm{j}} = \left[\begin{array}{c|c} \mathbf{R} & \mathbf{d} \\ \hline \mathbf{0} & 1 \end{array}\right]_{4\times4} \quad (3)$$

This matrix tool is an integral part of VRM kernel to generate the variational geometric patterns (KPCs) from the nominal CAD input features. The inspection point is introduced within a kernel which measures the identified KFCs for the generated variational patterns. Thus VRM simulation builds a non-linear response function '*f*' which is Key Failure Characteristic considering geometric part variations. The mathematical model can be generalized as

$$KFCs = f\,(KPC_1, KPC_2, KPC_3, \ldots, KPC_n) \quad (4)$$

where, 'KFC' is the dimensional measure under consideration, while KPC_i $(i=1,2,\ldots,n)$ represents the functional geometric contributors.

The response function '*f*' translates the KPCs to the KFCs. Considering numerous variational models, we will not have just a single equation but a sequence of equations that translates the variational KPCs to the KFCs. The second part of the root cause analysis module (RCAM) performs the factor analysis, to identify the contribution of each input KPC towards the function '*f*'. This is identified from the inverse mapping function '*g*'. Thus variation in top few KPCs reflects the variation in KFCs; hence a set of such KPCs is identified as the potential contributor towards the root cause.

Step 4: Developing Corrective Actions & Preventive Actions

As the sensitivities of each KPC is identified, i.e.,% contribution of each KPC, the upper and lower limits and statistical distribution of the geometric dimension of significant KPC/KPCs obtained from factor analysis can be calculated to avoid the observed Key Failure Characteristics. Thus a tolerance range for critical design parameters (DPs) is defined to reduce the observed warranty failure patterns considering the process capability. Hence tolerance band is redesigned for the identified significant set of KPC to avoid Warranty Failure Region (WFR). As a part of corrective action; modified GD&T is incorporated into the existing design through engineering change. Also modified design is verified by conducting validation tests. As a preventive measure design guideline and DFMEA is re-examined with the feedback from the observed failure modes in order to avoid them in future product designs.

4. Industrial Case Study

The methodology for identifying the root cause, described in previous section is demonstrated with a case study on warranty failure of automotive ignition switch. The data used in this case study pertains to issue of "sticking ignition switch" used for starting the passenger vehicle. The issue of ignition keys feeling "sticky", i.e., not having a free feel to its operation in clockwise and counter-clockwise movement.

However under subjective examination, and "sticking", i.e. staying in the START position, the switch is incapable of returning to the ignition (IGN) position when the key is released. Due to the possibility of sticking ignition switch staying in START position lead to starter motor overrun causing consequential failure. Thus issue point towards electrical failure in electro-mechanical system due to mechanical parameters i.e. tolerance of the internal components and subassemblies.

Step 1: Identifying Critical Warranty Failures

Ignition Switch was identified for deep-dive investigation from Walk-Home and CRM complaints at major automotive OEM. The higher levels of customer complaints related to ignition switch were reported at call-centers and Dealers. For e.g. Complaint - Starting Problem - Diagnosis - Starter Motor burnt by overrun due to key not returning to IGN from START position. Also other information used to reach component level investigation from customer complaints usually reported with system level descriptions e.g., starting problem, sticky key etc.

Step 2: Identifying Key failure Modes

To identify the key failure modes, a batch of ignition switches from the vehicle, many of which have been found to stick in the "start" position were examined. The batch specimens are classified into three different categories: (i) known to be faulty i.e. "sticky"; (ii) suspected faulty; and (iii) without any fault. The non-destructive testing using X-ray computed tomography (CT) is performed on such batch specimens to image the internal geometry of the mechanism. The specimen under examination was locked in the ignition position to identify the possible mechanical interference within the switch components which might be causing the device to catch.

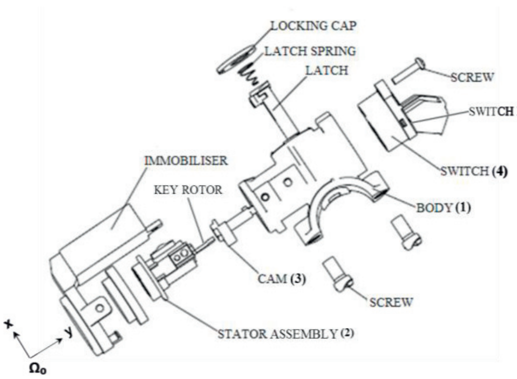

Figure.4. Exploded view of Ignition Switch assembly components

To understand the case, component parts of the switch assemblies are shown in the exploded view in Figure 4. The observation from non-destructive testing yielded different failure modes thus explaining failure mechanisms observed in warranty claims. The detailed sectional scan view in Figure 5 explains the failure modes observed in faulty ignition switches which differentiates it from the good samples. The key failure modes identified from the observations were: (i) stator assembly moving axially within the body creating a gap; (ii) deteriorated cam and key rotor engagement causing jamming; (iii) cam to body contact creating interference due to misalignment of cam.

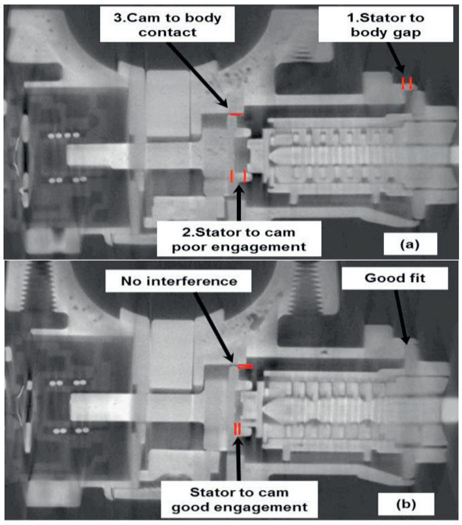

Figure.5. Sectional view of Ignition switch (CT scan)

(a) faulty; (b) without any fault

The second failure mode, i.e., poor engagement between stator to cam is identified as the most common failure mode, since it accounts for majority of reported failures. Hence interference between the cam and stator engagement is the KFC for performing the VRM simulation.

Step 3: Root Cause Analysis (RCAM) using VRM

Nominal CAD data for the ignition switch was arranged as a single structure. The data is exploded and reassembled into the individual component parts as listed in the 2D Drawing shown in Figure 6. The important component parts in the assembly are identified and labelled as ID=1, 2,…, 5 to build the DFC diagram which links the geometric features of the mating components ,i.e., functional KPCs. As explained in the DFC shown in Figure 6, J_i (i=1, 2, 3,..,8) represents the assembly joints in the existing product assembly. F_{ij} (i= joint ID, j=components ID) represents the geometric features (KPCs) of the identified mating components within the assembly.

Joint J_4 which links the geometric features F_{42} & F_{43} is the KFC as it measures the fit between the stator and the cam which is identified as critical warranty failure mode in Step 2. Initial configuration data is generated for each geometric feature F_{ij}, which is fed as the input to VRM kernel. For e.g. to model the feature 'F_{43}', which is a cylindrical type the input data is illustrated by:

- LINE.F43.N= [0 -1 0]
- VERTEX= [480.9 300.9 579.0; 480.9 297.7 579.0]
- DATUM= 'F53'
- TOL=T (8)
- MV= [0 *para [1] para[2]* 0 *para [3] para[4]*]
- MEASURE= [480.9 297.7 583.9]

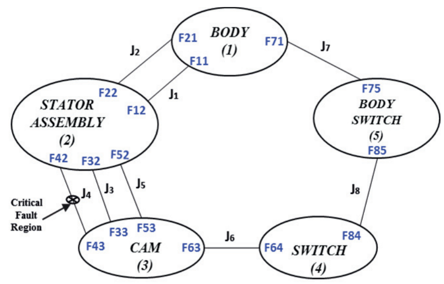

Figure.6. Datum Flow Chain Diagram for Ignition Switch

where, N defines the feature normal vector, VERTEX defines the points belonging to the outer boundary of the feature; for cylindrical feature the upper and lower points of the cylinder are defined. DATUM defines the datum reference feature for the input feature; TOL defines the geometric tolerance, MV defines the variational parameters. Each feature is parameterized with 6 variational parameters, 3 translations and 3 rotations. More specifically, planar features account 3 parameters, whereas 4 parameters are enough to parameterize cylindrical features. The provided example assumes that "para" contains the 4 parameters for the cylindrical feature, named "F43". The MEASURE defines the inspection point at which KFC is measured.

The VRM simulation generates output variation at the inspection points by statistically simulating variations of input feature parameters. A Monte Carlo sampling was adopted for that purpose. Potential root causes related to the assembly sequence has been also investigated. In fact, as shown in Figure 7(b) when mating constraints are not simulated (only variational features are accounted) the sensitivity on KFC is slightly different than the one obtained with the whole set of mating joints (see Figure 7a).

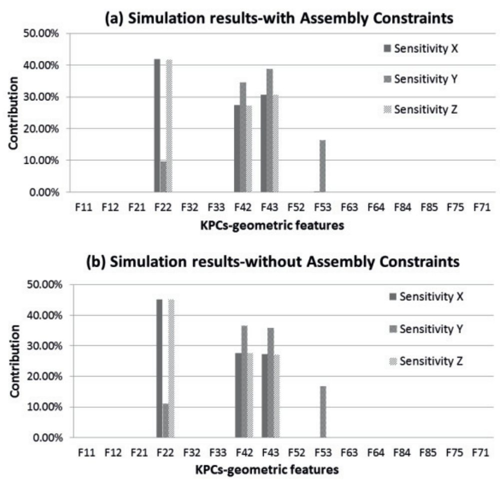

Fig.7. Simulation results-(a) with Assembly Constraints; (b) without Assembly Constraints.

Further sensitivity analysis evaluates the contribution of each KPC feature towards the identified key failure characteristic. As evident from the Figure 7, the geometric feature 'F_{22}' is more sensitive in X and Z directions and hence a major contributor towards the observed faulty characteristic between feature 'F_{42}' and 'F_{43}'. Feature 'F_{22}' represents the planar contact between stator assembly and the body as pointed by failure mode 1 in Figure 5(a). This concludes that variation in feature 'F_{22}' is the preliminary root cause as it controls the stator to body gap. The set of $KPC = \{F_{22}, F_{42}, F_{43}\}$ is identified as potential root cause of failure with different sensitivity levels for each feature.

Step 4: Developing Corrective Actions & Preventive Actions

Based on the generated Assembly Response Function (ARF) during Step 3 which links KFCs with KPCs, the designer can redesign the tolerance band for the observed set of KPC considering the process capability and optimize the assembly sequence of the ignition switch components.

5. Conclusion

The approach presented in this paper gives an analytical methodology to perform the root cause diagnosis of product service failures. The sensitivity index presented here identifies the interaction between the design parameters (DP) and the key warranty failure modes reported from service. The results can be adopted by product design team to (i) identify the root cause for in-tolerance product design faults; (ii) correct the GD&T for such faults; and (iii) based on feedback improve the quality of future product design.

The current research can be extended by proposing a robust methodology for developing corrective actions by identifying the optimum tolerance band levels for critical design parameters to minimize the fallout rate of products within design tolerances (in-specs) due to service failures.

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