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Root Cause Analysis of Product Service Failures in Design -A Closed-loop Lifecycle Modelling Approach

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Abstract

A number of industries including aerospace, telecom and automotive incur warranty and product return costs due to product malfunctions in service, which can also negatively impact customer satisfaction and loyalty. Product failures, which occur in service, are often caused by root causes at design or at manufacturing phases. Therefore a novel inter-loop modelling framework is needed which takes information from different phases to determine root causes and corrective actions. This goes beyond current intra-loop methods such as design optimization, statistical process control etc., which uses information from a single phase to address failures in the same phase. However, inter-loop modelling poses the challenge of integrating heterogeneous data from different phases of lifecycle with product and process models to determine failure root causes and corrective actions. To deal with failures in service, this paper proposes Closed-loop Lifecycle Modelling approach, specifically integrating information from service and design. Related work on fault diagnosis and corrections is also reviewed in the context of intra and inter loops of product lifecycle.

The proposed methodology addresses root cause analysis (RCA) of service failures caused due to dimensional variations of product features. RCA identifies critical geometric features of internal components, which affects dimensional variations of product features. This is done by integrating warranty data from service to design models such as CAD, Geometric Dimensioning & Tolerancing (GD&T) etc. Steps of the methodology include: (i) identification of faulty product features from the Ishikawa diagram of the failure reported in warranty; (ii) variation simulation analysis of geometric features of internal components; (iii) determination of critical geometric features affecting faulty product feature via surrogate modelling of dimensional variations; and (iv) analyzing sensitivity of faulty product features on critical geometric features. The proposed Design-Service inter loop is demonstrated by an industrial case study of automotive ignition switch and *'Sticky Key'* service failure. RCA of *'Sticky Key'* issue identifies critical geometric features and their sensitivity in affecting the faulty product features, which cause the failure.

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Keywords: Product service failures; Product Lifecycle; Root Cause Analysis; Functional Requirements; Design Paramters; Variation Simulation; Surrogate modelling; Sensitivity analysis

1. Introduction

Product failures in service such as warranty and No-Fault-Found (NFF) failures result in significant costs of warranty and product returns in industries such as automotive, aerospace, mobile phones etc. [1][2]. NFF-related problems negatively affect customer satisfaction in terms of product safety and reliability, and contribute to increased product life-cycle cost [1]. Therefore, root cause analysis (RCA) and corrective actions (CA) of product failures in service is important.

In the service phase, unexpected product malfunctions whose root cause cannot be diagnosed after service checks are categorized as No-Fault-Found (NFF) failures. Service failures are often caused by root causes at design or at manufacturing phases. For example, erroneous characterization of customer attributes during early product development increases the risk of unexplored interactions during the design phase [2]. Such interactions may go

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unnoticed by designers and increase the risk of failure regions inside defined design tolerances (*in-tolerance* failures). In the manufacturing phase, one of the reasons, why unexpected challenges might arise is due to process capability being commonly not taken into consideration concurrently with product and process design. Thus, the impact that process variations have on final product quality may cause a product's non-conformance. The lack of concurrency demands the need to move from just part and product tolerancing (driven by seminal concept of part interchangeability) to simultaneous parts/product and process tolerancing (process-oriented tolerancing) [3].

Root causes of service failures are often in design and manufacturing. Therefore, to address root causes of service failures, it is necessary to develop analytical methods based on inter-loop modelling which integrates heterogeneous data from different phases of lifecycle with product and process models. This research proposes a Closed-loop Lifecycle Modelling approach to deal with service failures by specifically integrating warranty data with design models. The remainder of the paper is organized as follows: Section 2 describes the framework Closed-loop Lifecycle Modelling. Related work on fault diagnosis and adjustments are reviewed in the context of the proposed framework. Section 3 presents root cause analysis of service failures specifically linking warranty data with design models. This is followed by an industrial case study in Section 4. The paper ends with remarks on future work in Section 5.

2. Closed-loop Lifecycle Modelling

The loops of self-resilient production system are classified as intra-loop and inter-loop based on availability of data from same or different phases of PLM respectively. Fig. 1 shows the closed-loop framework. The intra loop refers to integration of data with product and process models from same phase of PLM such as SPC which uses manufacturing data for monitoring purposes. The inter-loop refers to integration of data with product or process models obtained from more than one phase of PLM such as addressing service failures using the approach proposed by Mannar et al. [2], which uses data from manufacturing and service phase of PLM.

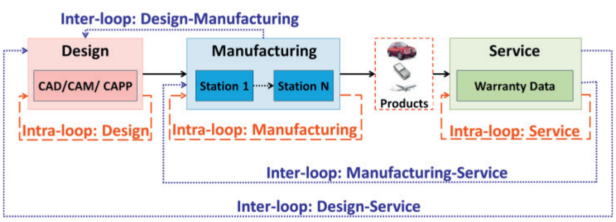

Fig. 1. Framework for Closed-loop Lifecycle Modelling

2.1. Intra loops in PLM

In design phase, product simulation generates data on design parameters (DPs) satisfying pre-defined functional requirements (FRs). Methodologies have been developed to enable design changes and optimization by modelling the relationship between critical DPs to FRs and critical process variables (PVs) to DPs [4,5].

In manufacturing phase, the intra-loop consists of continuous data of DPs and PVs obtained using in-line and/or off-line measurements of products and processes during production. The intra-loop in manufacturing is used to addresses out-of-tolerance 6-sigma failures using SPC techniques [6,7]. The monitoring capability can be further integrated with process models to enhance the intra-loop capability of the production systems for fault diagnosis and adjustments [8].

Intra-loop in service consists of warranty data and failures data which are analyzed to send feedback to OEMs for setting economic warranty reimbursements to customers, estimating field reliability of products and changing design to address service failures [9]. Warranty data is also used to improve performance of service centres by generating pre-alerting rules to diagnose product failures from customer complaints [10].

2.2. Inter loops in PLM

The Design-Manufacturing inter-loop integrates information from manufacturing with design to evaluate and improve diagnosability and adjustability of products thus reducing test time of failures in case of uncertain faults [11].

In Manufacturing-Service inter-loop, the Functional Region Localization (FRL) methodology [2] integrates manufacturing and service information to identify and isolate in-tolerance fault regions in DPs. Prakash et al. [12] determine the necessary process adjustment to reduce number of products falling in NFF fault region.

For Design-Service inter-loop, there is need for analytical method to identify root causes of service failures by integrating warranty failures with design models. Shrouti et al. [13] maps service failures in mechanical assemblies with faulty FRs such as gaps or contacts between internal components. Simulation of geometric DPs is done to model variation in FRs. The current research extends this work by (i) demonstrating the use of fault trees to identify faulty FRs for a given service failures; and (ii) identifying critical DPs related to faulty FRs; and (iii) developing analytical surrogate model linking faulty FRs as a response of critical DPs. Corrective actions via design adjustments such as mean shift and tolerance reduction of DPs will significantly benefit from the information on critical DPs and analytical surrogate model of faulty FRs. Section 3 describes a methodology of root cause analysis (RCA) of service failures by integrating customer complaints and parts replaced information from warranty with design models such as Ishikawa diagram, CAD, GD&T and variation simulation analysis. RCA identifies critical geometric DPs whose dimensional variations results faulty FRs. Sensitivity of faulty FRs on critical DPs is also determined. Fault Corrective action by tolerance re-allocation depends on identification of critical DPs and sensitivity analysis to minimize dimensional variations in faulty FRs.

3. Methodology

The proposed methodology focusses on addressing direct or consequential failures caused by dimensional variations in rigid body assemblies. Failures manifest as violation of functionality which depends on dimensional behavior of Functional Requirements (FRs) such as gaps, contacts etc. FRs are achieved in product design by geometric Design Parameters (DPs) whose dimensional variations affect FRs. When FRs do not satisfy the specification for normal functioning of the product, failures occur. For example, if a clearance or contact between two mating surfaces is required for normal functioning, then interference between the two surfaces will cause failure. The proposed methodology first identifies FRs which are responsible for the faulty functionality. Next, critical DPs whose dimensional variations result faulty FRs, are determined and sensitivity analysis is done between FRs and critical DPs. Identification and sensitivity analysis of critical DPs is the key input required for tolerance re-allocation to correct the failure. The steps of the root cause analysis methodology are shown in flowchart of Fig. 2.

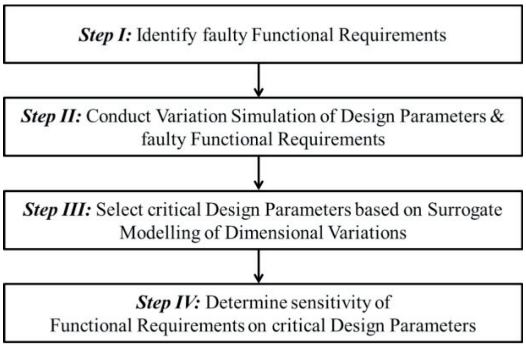

Fig. 2. Root Cause Analysis of Product Service Failures caused by Dimensional Variations

The steps of the proposed methodology are detailed as follows:

Step I: *Identify faulty Functional Requirements-*

Warranty data, obtained from service agents such as dealers, call centres etc., is analyzed to determine customer complaints and parts being replaced by dealers. A Pareto analysis of frequency of customer complaints or cost of replaced parts is performed [13] to determine critical issues and related components that require Root Cause Analysis (RCA) and Corrective Actions (CA). Next, Ishikawa diagram of the failure is referred to link customer complaints with faulty product features, which are further translated to dimensional FRs such as gaps, contacts etc. from CAD models. Besides, a sample of failed parts is subjected inspection and measurement to confirm that faulty FRs, which are identified in the previous step, do not conform specifications of normal functionality in the sample.

Step II: *Conduct Variation Simulation of Design Parameters & faulty Functional Requirements-*

Simulation of dimensional variation of DPs and faulty FRs are done in the following steps:

- *Model DPs as variational features & setup Assembly Constraints*- The Datum Flow Chain (DFC) [13] is applied to determine all sub-assemblies and parts, from which functional geometric features are identified based on nominal CAD model of the parts. DPs are modelled as the planar and cylindrical features. Variations based on dimensional torelancing will be applied to the DPs to generate FRs. Next Assembly Constraints are introduced between the DPs to define mating surfaces.

- *Simulate DPs & FRs by Variation Response Method (VRM)* - Variational geometric features (DPs) and Assembly Constraints, specified in the previous step forms input to VRM [14], which generates geometric variations of DPs based on Monte-Carlo Simulation. Optimal assembly configuration for a set of DPs is determined and FRs are measured as clearance or interference between pre-defined inspection points on the planar or cylindrical features. Co-ordinates of inspection points are expressed in the global co-ordinate system of the nominal CAD model using 4×4 homogenous transformation matrix, which is defined as

$$\mathbf{T_{0i}} = \begin{bmatrix} \mathbf{R_{0i}} & \mathbf{p_{0i}} \\ \mathbf{0} & \mathbf{1} \end{bmatrix} \quad (1)$$

where, $\mathbf{R_{0i}}$ is 3×3 rotation matrix and $\mathbf{p_{0i}}$ is 3×1 displacement vector.

If $\mathbf{P_0}$ and $\mathbf{P_i}$ are positions of the inspection point in global and assembly co-ordinate frames respectively then,

$$\mathbf{P_i} = \mathbf{T_{0i}}\,\mathbf{P_0} \quad (2)$$

and

$$\mathbf{P}_0 = \mathbf{T}_{0i}^{-1}\mathbf{P}_i \quad (3)$$

SVA-TOL is run for 'N' times and DPs and FRs are recorded for each run.

Step III: *Select critical Design Parameters based on Surrogate Modelling of Dimensional Variations-*

Based on the observations of variation simulation, this step develops a surrogate model of DPs dimensional variations which expresses FRs as response of the DPs. The surrogate model can be represented as follows,

$$FR_k = f_k(DP_1, DP_2, \ldots DP_p) \quad (4)$$

$\forall$ k=1,2,…,n.

Since the DPs operates non-linearly, surrogate model up to d[th] order with interactions is considered, where $d \geq 1$. Any term in the surrogate model can be represented as

$$t_l = DP_1^{w_1} DP_2^{w_2} \ldots DP_p^{w_p} \quad (5)$$

where, $w_1 + w_2 + \ldots + w_p = d' \;\; \forall \;\; d' = 1,2,\ldots,d$.

Total number of terms in a surrogate model up to d[th] order is

$$t_{Total} = p + p^2 + \ldots + p^d = p\frac{p^d - 1}{p - 1} \quad (6)$$

The surrogate model of Equation 4 is trained using data on FRs and DPs generated by variation simulation of Step II. The model is fitted by minimizing residual sum square (RSS) error using Least Squares Regression. For FR_k, RSS based on full training data is given as and using set of terms **T** to build the surrogate model is given by,

$$RSS_k^T = \sum_{j=1}^{N}(FR_{kj} - \hat{FR}_{kj})^2 \qquad (7)$$

where FR_{kj} and $\hat{FR}_{kj}$ are training and fitted values respectively. For developing surrogate model of n^{th} order, all terms lower order terms are selectively added to the model before considering higher order terms. Terms are entered in the model through Forward selection-Backward elimination method [15]. The criteria for selection and elimination of a term are the decrease in mean prediction error (MPE_k) upon inclusion or exclusion of the term. MPE_k is determined by v-fold cross-validation [16], which divides training data in v folds. Surrogate model is trained using data from all but one fold. RSS is calculated based on the fold, which is left out for model training. For a model based on a set of terms **T**, mean prediction error is denoted as MPE_k^T .

If **T** is a set of terms selected so far, a new term t is selected if $MPE_k^{T\cup\{t\}} < MPE_k^T$. Similarly, term $t \in \mathbf{T}$, is eliminated if $MPE_k^{T-\{t\}} < MPE_k^T$. Therefore, Forward selection-Backward elimination process will end with critical terms left in the final set **T**. DPs appearing in one or more terms of final set **T** are critical ones.

Step IV: *Determine sensitivity of faulty FRs on critical DPs-*

Sensitivity analysis is done by taking partial derivative of faulty FRs on critical DPs. The surrogate model of dimensional variations, obtained from previous step, is an analytical response function for FRs in terms of DPs. The function *'f'* is derivable for all DPs over the domain defined by tolerance allocation in Step II. Sensitivity of FR_k on DP_i is given by

$$Sensitivity_{ki} = \frac{\partial f_k(DP_1, DP_2, \ldots DP_p)}{\partial DP_i} \qquad (8)$$

$\forall$ k=1,2,…,n and $\forall$ i=1,2,…,p.

4. Industrial Case Study

The Root Cause Analysis (RCA) methodology is demonstrated by a case study on automotive ignition switch. Fig. 3 presents an exploded view of ignition switch showing the individual parts 1-5.

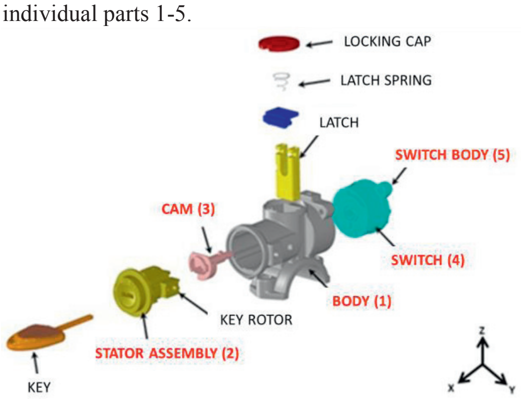

Fig. 3. Exploded view of ignition switch with individual parts 1-5

A direct customer complaint is *'Sticky key'* whereby ignition switch lacks a free feel of operation when turned clockwise or anti-clockwise. When the key is turned from *Ignition* to *Start* position, it is incapable of returning to *Ignition* once released. Overstay of the key at the *Start* position also allows excessive current to flow through starter motor resulting in *'Starter motor burnout'*, which is an electro-mechanical failure *i.e.* consequential electrical failure caused by dimensional variations of internal components of the ignition switch. Therefore for *'Starter motor burnout'* cases both starter motor and ignition switch are replaced by service centres.

The steps of the RCA methodology are described as follows:

Step I: *Identify faulty Functional Requirements-*

Warranty data is analysed to find *Sticky Key'* and *'Start motor burnout'* incidents reported by customers and components replaced by service centres. Ignition switch is found to be replaced for both issues. Ishikawa diagram of *'Sticky key'* problem as shown in Fig. 4 identifies misalignment of stator within the body.

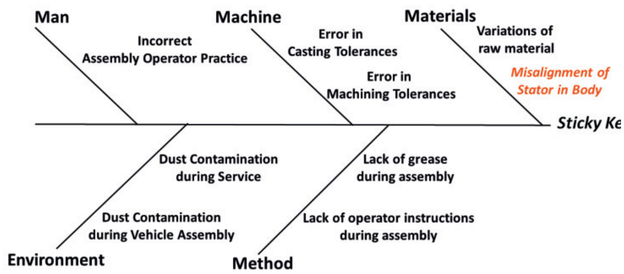

Fig. 4. Ishikawa diagram of *'Stick key'* failure in ignition switch

X-Ray Computer Tomography (CT) scanning of faulty ignition switch shows that misalignment of stator within the body causes lock to cam interference [13]. This is illustrated in Fig. 5.

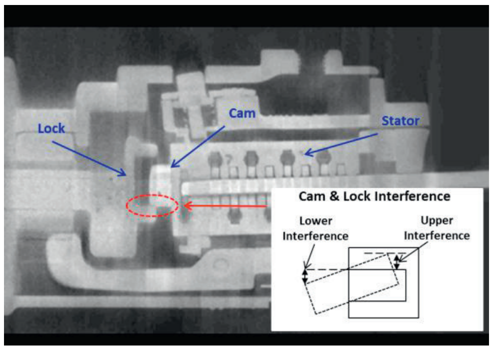

Fig. 5. Lock & cam interference due to stator (Chetan et. al, 2012) [13]

Therefore, the gap between lock and cam is the geometric FR, which in case of clearance allows free rotation of cam inside the lock but causes *'Sticky key'* issue in case of interference.

Step II: *Conduct Variation Simulation of Design Parameters & faulty Functional Requirements-*

Nominal CAD of the ignition switch is referred to develop datum flow chain, which is shown in Fig 6. F_{ab} are geometric features that affect assembly joints J 1-8. The faulty FR is joint J4. Let (α, β, γ) be the rotational DPs and (Δx, Δy, Δz) be the translational DPs for any identified critical feature. For example, feature F42, is modelled as a cylindrical feature with two DPs: (i) rotation about Y-axis (β_{F42}); and (ii) rotation about Z-axis (γ_{F42}), given the cam cylinder axis is parallel to X-axis of global co-ordinate frame in the CAD model.

The gap between cam and lock is further modelled as two geometric FRs: (i) FR_1 – Upper clearance at the top of the cam; and (ii) FR_2 – Lower clearance at the bottom of the cam. VRM is run 3000 times simulating DPs, FR_1 and FR_2. Negative values of clearance indicate interference, which causes jamming in the lock and cam.

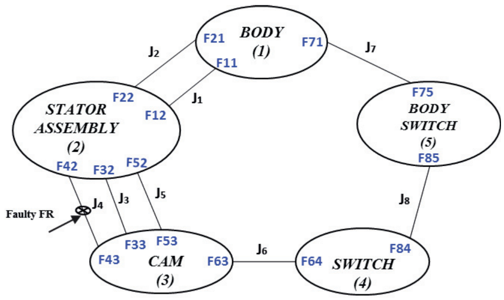

Fig. 6. Datum Flow Chain of Ignition switch (Chetan et. al, 2012) [13]

Step III: *Select critical Design Parameters based on Surrogate Modelling of Dimensional Variations-*

The case study considers surrogate model up to 2nd order (d=2). Forward selection-backward elimination method selects critical DPs based on Mean Prediction Error, which is determined by 5 fold cross-validation. The final surrogate models are build using the critical DPs as shown in Eqs. 9 and 10.

$$FR_1 = 1.16\times10^{-5} + 1.61\beta_{F42} - 1.63\beta_{F43} + \beta_{F43}(2.47\beta_{F11} - 4.66\beta_{F43}) \quad (9)$$

$$FR_2 = -4.22\times10^{-4} - 1.58\beta_{F42} + 1.56\beta_{F43} + \beta_{F11}\Delta x_{F21}(37.01\Delta x_{F21} - 45.91\Delta x_{F53}) \quad (10)$$

Table 1 summarizes the results of Surrogate Modelling of Dimensional Variations.

Table 1. Results of Surrogate Modelling of Dimensional Variations

Functional Requirement	No. of Total /Critical DPs	Critical DPs	RSS
Upper clearance (FR_1)	24/3	β_{F11} , β_{F42} & β_{F43}	0.507
Lower clearance (FR_2)	24/5	β_{F11} , Δ_{F21} , β_{F42} , β_{F43} & Δ_{F53}	0.759

Fig. 7(a) and (b) shows the surrogate models with respect to two DPs, keeping the rest as constant at their mean values. Isolines of the surrogate models are shown in Fig. 8(a) & (b).

Step IV: *Determine sensitivity of faulty FRs on critical DPs-* Sensitivity analysis is done based on partial derivatives of the surrogate model with respect to (w.r.t) DPs. Examples of partial derivatives of FR_1 and FR_2 is given in Eqs. 11 and 12.

$$\partial FR_1 / \partial\beta_{F43} = -1.63 + 2.47\beta_{F11} - 9.32\beta_{F43} \quad (11)$$

$$\partial FR_2 / \partial\Delta x_{F21} = \beta_{F11}(74.02\Delta x_{F21} - 45.91\Delta x_{F53}) \quad (12)$$

Equations 11 and 12 permits sensitivity analysis over a continuous domain and therefore give greater flexibility than point-based approach [13].

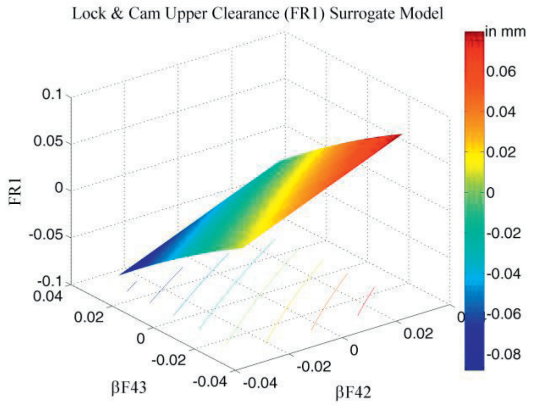

Fig. 7(a). Surrogate Model of Lock & Cam Upper Clearance

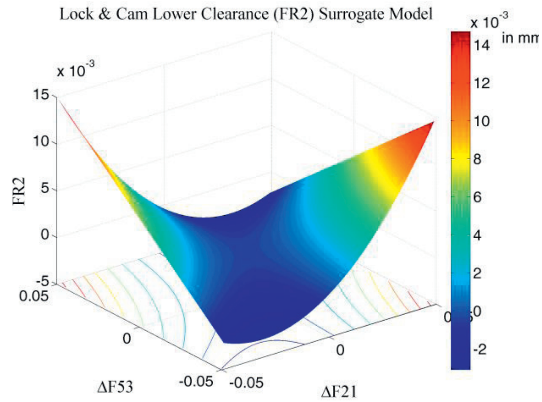

Fig. 7(b). Surrogate Model of Lock & Cam Lower Clearance

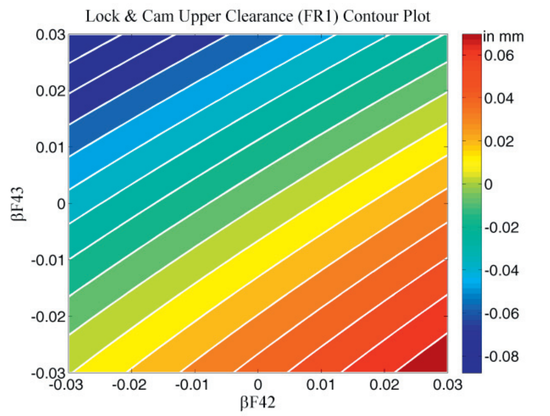

Fig. 8(a). Isolines of Surrogate Model of Lock & Cam Upper Clearance

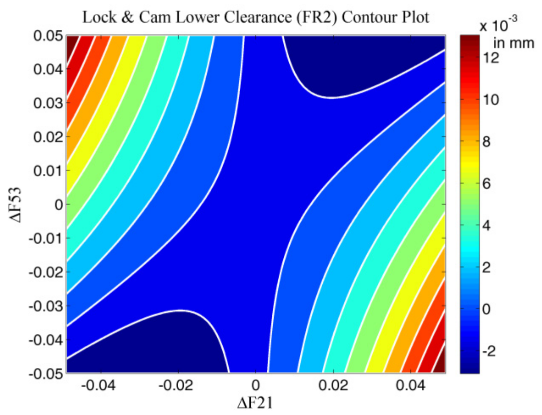

Fig. 8(b). Isolines of Surrogate Model of Lock & Cam Lower Clearance

Discussion of Results- The significance of the results of the case study is discussed in the context of the objectives of the RCA methodology as follows:

- *Identification of critical DPs affecting faulty FRs* – The surrogate modelling approach narrowed down to 3 and 5 critical DPs from a total of 24 for FR_1 and FR_2 respectively. Reducing number of DPs is crucial as tolerance re-allocation incurs cost, which will be less when lesser DPs are adjusted.

- *Sensitivity Analysis of faulty FRs w.r.t critical DPs*- The surrogate models expresses the faulty FRs as analytical response functions of critical DPs. This allows sensitivity analysis over a continuous domain. This provides greater flexibility than point-based sensitivity analysis [13] in adjusting tolerances by setting constraints.

In summary, the outcome of the proposed methodology is a significant input for corrective actions via design adjustments. Information about critical Design Parameters (DPs) and analytical surrogate model of faulty Functional Requirements (FRs) will enable cost-driven optimization on critical DPs to determine mean shift and tolerance reduction of DPs, which minimize production yield of faulty FRs.

5. Conclusion & Future Work

The RCA methodology described in this paper provides a systematic approach of addressing service failures by integrating warranty data and design models. Future work can utilize the results of this paper in the following ways:

- The effect of dimensional variations of DPs on FRs is represented by analytical closed-form surrogate models, which can be developed offline. Therefore, surrogate models are computationally efficient alternative to variation simulation in applications that require frequent execution of the later.
- For service failures, corrective actions such as design optimization, tolerance reallocation significantly benefit from identification of critical DPs and sensitivity analysis of faulty FRs over continuous domain providing. The current methodology can be extended to generation of corrective action by optimal tolerance reallocation.
- The current work can also be extended for process control which also has same requirements as the proposed RCA methodology viz. (i) closed-form representation of relation between product features and control parameters; (ii) selection of critical control parameters; and (iii) sensitivity analysis of product features w.r.t critical control features.

Overall, the approach of surrogate modelling of dimensional variations of control parameters such as DPs in design stage has potentially significant applications in RCA and CA of service failures as well other design and manufacturing related tasks.

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