Grey Relational Analysis in PFMEA for Camshaft Sub-Assembly Failure Prediction

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Abstract- The objective of the research paper is to reduce the risk of process potential failures and to prioritize the risk of failure of sub-assembly of camshaft. A Process Failure Mode and Effects Analysis (PFMEA) is used for the risk analysis for process failure before it happens. Typically, the risk priority in the PFMEA is performed using risk priority numbers (RPNs) that can be determined by evaluating three factors: occurrence (O), severity (S), and detection (D). It was observed that the conventional PFMEA based on crisp RPN is not supportive and robust enough in priority ranking of potential failure modes. To overcome this drawback we applied Grey relational analysis (GRA) to calculate the grey relation coefficient. The ranking of the risk of process failure modes determined by grey theory. For feasibility of GRA in PFMEA are verified by using it to deal with failure risk evaluation of process failure modes for sub assembly of camshaft.

Keywords-GRA, PFMEA, Severity, Occurrence, Detection, Camshaft Sub-assembly.

I. INTRODUCTION

In the highly competitive environments, manufacturing is considered as the backbone of any industrialized nation. Today, manufacturing industries are phasing challenges in quality, time and cost in competitive market. This challenge encountered by process, design, or maintenance failures. This failure creates a major impact on the product quality and productivity. The effects of a failure are focused on manufacturing operations, processes and impact on customer. There are several techniques developed to perform to risk assessment or prioritization. PFMEA is one of the most widely used risk assessment tool for identifying and prioritizing risk of potential failure modes of process or manufacturing operation (Stamatis, 1995). PFMEA is a type of FMEA which is looks at each process step to identify risks and possible failure from many different sources. A Process Failure Modes and Effects Analysis provide a structured, qualitative, analytical method which define and analyse to brainstorm answers to such questions as:

1. How can this process, function, facility, or tooling fail?
2. What effect will process, function, facility, or tooling failures have on the end product (or customer)?
3. How can potential failures be eliminated or controlled?

This FMEA was first proposed by National Aeronautics and Space Administration (NASA, U.S.A.) in 1960. Then, it was adopted and promoted by Ford Motor in 1977. Today, FMEA has been used in world wide spectrum in the areas of Chemical, Aerospace, Military, Automobile, and Electrical, Mechanical and Semiconductor industries (Chang and Cheng, 2011). The risk computation of different potential failure modes using conventional PFMEA has been done by developing risk priority number (RPN). The conventional RPN is the value obtained by the product of three components, i.e. the occurrence probability of a failure mode (O), the severity of the failure mode (S) and the delectability of the failure mode (D). Higher the value of the RPN higher is the risk associated with the corresponding failure mode. The purpose of conventional RPN is to prioritize the failure modes of a process, so that the available resources can be effectively allocated. More risky failure modes will be tackled with more resources in terms of effort, time and cost. Mathematically the conventional RPN can is expressed as:

$$RPN = S \times O \times D \quad (1)$$

However the precise values of S, O and D are difficult to be predictable by experts, different combinations of S, O and D may get the same result, and the relative importance of S, O and D is not taken into consideration. To enhance and overcome these reactions of the conventional FMEA, Grey theory is presented in FMEA, which make the outcomes more sensible and an adaptable impression of the genuine circumstance.

II. LITERATURE REVIEW

During the beginning stage of this work, it was realized that FMEA/PFMEA technique has been applied widely in certain parts of the world. Dale and Shaw (1990) investigated the reasons for the usage of FMEA and found that majority of the manufacturing companies used PFMEA because of the mandatory requirement of their customers. The literature survey is the brief review of the accredited research on process failure mode and their drawbacks. In this paper, literature research on PFMEA risk assessment for the prioritization of failure modes.

Grey theory and Fuzzy logic applied in FMEA for tanker equipment failure prediction. Another fuzzy FMEA, which permits the hazard factors and their relative weights to be assessed in a linguistic way as opposed to precisely. Xu et al. (2002) developed a fuzzy-logic-based FMEA technique and a prototype assessment expert system for engine system, in which a fuzzy expert assessment is integrated with the proposed system to overcome the potential difficulty in sharing information among experts from various disciplines. Abdelgawad and Fayek (2010) used fuzzy logic and fuzzy analytical hierarchy process (AHP) to address the limitations of traditional FMEA, and the results confirmed the capability of fuzzy FMEA and fuzzy AHP to address several drawbacks of the traditional FMEA application. Chin et al. (2008) discussed the development of a fuzzy FMEA method based on a product design system, carried out research studies to explore the applicability of fuzzy logic and knowledge-based systems technologies to the competitive product design and development, with an emphasis on the design of high quality products at the conceptual design stage. Braglia et al. (2003b) proposed a multi-attribute decision-making approach called fuzzy TOPSIS (technique for order preference by similarity to ideal solution) approach for FMECA (failure mode effects and criticality analysis), which allows for the risk factors O, S, and D and their relative importance weights to be evaluated using triangular fuzzy numbers. Garcia and Schirru (2005) presented a fuzzy data envelopment analysis approach for FMEA in which typical risk factors O, S and D were modelled as fuzzy sets. Pillay and Wang (2003) proposed a fuzzy rule base approach to avoid using traditional RPN, and the membership functions of the three risk factors O, S and D were set up first. The traditional FMEA method cannot assign different weights to the risk factors of O, S and D, and therefore may not be suitable for the real situation. Introducing grey theory to the traditional FMEA enables engineers to allocate the relative importance to the risk factors S, O and D based on the research and their experience. Grey theory proposed by Deng (1982), deals with making decisions characterised by incomplete information, and explores system behaviour using relational analysis and model construction. Grey theory can be applied to analyse relationships between discrete quantitative and qualitative series, whose components are existent, countable, extensible and independent. Since factors of FMEA have all of these properties, therefore, grey theory can be applied to FMEA. The focus of this research paper is to identify assembly process failure risk using PFMEA combined with grey theories. The rank of camshaft sub assembly failure modes can be obtained by grey theory, and the results can be used for decision-making concerning the inspection. This in turn can help to optimise the process failure.

III. METHODOLOGY

Grey theory was firstly introduced by a Chinese professor Julong Deng of Huazhong University of Science and Technology in 1982. It's main aim to make decisions under incomplete information. It is shown that Grey theory is superior to other methods in theoretical analysis of systems with uncertain information and incomplete data samples. The major advantage of Grey theory is that it can handle both incomplete information and unclear problems very precisely.

Grey analysis uses the factors (Severity, Occurrence and Detection) to prioritize the failure mode with a different mathematical step. Grey analysis is used because of the prioritization of failure modes with more accurate values than of conventional PFMEA approach. The prioritization of the failure modes for grey theory helps in the present study needs high accuracy. Step by step process for the application of the Grey Relational Analysis to PFMEA.

Step1: S, O and D taken from the conventional PFMEA table.

The linguistic terms describing the decision factors of S, O and D taken from the severity, occurrence and detection table.

Step2: Establish of Comparative Series

An information series which includes value of likelihood of Severity [Xi (1)], Occurrence [Xi (2)] and Detection [Xi (3)] is the comparative series. The comparative series applied to FMEA is given as:

$$X_i(k) = [X_i(1) \quad X_i(2) \quad X_i(3)] \qquad (2)$$

Where, k = 1, 2 and 3 (Number of risk factors) and i= 1, 2,….n (n is the number of failure modes).

If all series are comparative series, the n information series was arranged in the matrix as given below, in which n is the number of failure modes;

$$X_i(k) = \begin{bmatrix} X_1(k) \\ X_2(k) \\ \cdot \\ \cdot \\ X_n(k) \end{bmatrix} = \begin{bmatrix} X_1(1) & X_1(2) & X_1(3) \\ X_2(1) & X_2(2) & X_2(3) \\ & \cdot & \\ & \cdot & \\ & \cdot & \\ X_n(1) & X_n(2) & X_n(3) \end{bmatrix} \qquad (3)$$

Step3: Establish of Standard Series

An objective series called as the standard series which was expressed as the following: Series notation: X0 (k) = {X0 (1), X0 (2), X0 (3)} (4)

In FMEA, the smallest score represents the smallest risk. Thus, the standard series should be the lowest score of likelihood of Severity, Occurrence and Detection factors. The purpose of defining standard series is to estimate the relationship between standard series and comparative series. The magnitude of this relationship is called as a

"Degree of Relation". As the Degree of Relation goes higher the score comes closer to the desired value.

Step4: Calculate the Different Sequence

The Degree of Grey Relationship, the difference between the scores of risk factors and scores of standard series should be calculated. The result of this calculation is expressed as the follows:

$$X_i(k) = \begin{bmatrix} \Delta_{01}(k) \\ \Delta_{02}(k) \\ . \\ . \\ \Delta_{0n}(k) \end{bmatrix} = \begin{bmatrix} \Delta_{01}(1) & \Delta_{01}(2) & \Delta_{01}(3) \\ \Delta_{02}(1) & \Delta_{02}(2) & \Delta_{02}(3) \\ & . & \\ & . & \\ & . & \\ \Delta_{0n}(1) & \Delta_{0n}(2) & \Delta_{0n}(3) \end{bmatrix}$$

(5) Where, i=1, 2, ……n (n is the number of failure modes).

Table 1: Criteria for severity ranking (S)

(Source: SAE J-1739, 2009)

Code	Classification	Effect
10	Hazardous Without Warning	Very high ranking - which affects safe operation.
9	Hazardous With Warning	Regulatory non compliance.
8	Very High	The product becomes inoperable, with loss of function - The customer is very dissatisfied
7	High	The product stays operable however the loss of execution - Customer disappointed
6	Moderate	Product stays operable however the loss of convenience /solace - Customer Discomfort
5	Low	Product stay operable yet loss of solace/convenience - Customer Slightly Dissatisfied
4	Very Low	Nonconformance by specific things – Noticed by generally customers
3	Minor	Nonconformance by specific things – Noticed by normal customers
2	Very Minor	Nonconformance by specific things – Noticed by particular customer
1	None	No Effect

Step5: Calculate the Grey Relationship Coefficient

The Grey Relationship Coefficient, three risk factors of the failure modes are compared with the standard series. The correlation coefficient is calculated as the following:

$$\gamma[X_0(k), X_i(k)] = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{i(k)} + \zeta\Delta_{max}} \quad (6)$$

where, X_0 (k); standard series, X_i (k); comparative series, i = 1, 2, 3…..n (n is the number of failure modes), k = 1, 2 and 3 (number of risk factor), Δ_{min} = minimum value of all Δ_i (k), Δ_{max} = maximum value of all Δ_i (k), ζ (0, 1) identifies coefficient and if affects the relative value of the risk without changing its priority. The value of ζ is 0.5.

Step6: Calculate the Degree of Relation

The degree of relation, first the relative weight of the risk factors should be decided. The relative weight used in following formulation is given below:

$$\tau_i(k) = \beta_k \sum_{3k=1}^{i} \Delta_i(k)$$

where, i =1, 2,….n (n is the number of failure modes), k =1, 2 and 3 (number of risk factors), β k = the weighting coefficient of the risk factors and

$$\sum_{k=1}^{3} \beta_k = 1.$$

Table 2: Criteria for Occurrence ranking (O) (Source: SAE J-1739, 2009)

Probability	Possible Failure Rates	Ranking
Very High: Failure is almost expected	≥1 in 2	10
	1 in 3	9
High: Generally associated with processes that have repeatedly failed	1 in 8	8
	1 in 20	7
Moderate: Generally associated with processes similar to previous processes which have experinced irregular failures, but not in main scope.	1 in 80	6
	1 in 400	5
	1 in 2000	4
Low: remote failures related with similar processes.	1 in 15000	3
Very low: Only remote failures related with roughly identical processes.	1 in 150000	2
Remote: Failure is unlikely	≤ 1in 1500000	1

Table 3: Criteria for Detection ranking (D) (Source: SAE J-1739, 2009)

Detection	Criteria	Ranking
Positively impossible	No known control(s) available to identify to failure mode	10
Very remote	Extremely remote probability current control(s) will identify the failure mode	9
Remote	Remote probability current control(s) will identify failure mode	8
Very low	Very low probability current control(s) will identify failure mode	7
Low	Low probability current control(s) will identify failure mode	6
Moderate	Moderate probability current control(s) will identify failure mode	5
Moderately high	Moderately High probability current control(s) will identify failure mode	4
High	High probability current control(s) will identify failure mode	3
Very High	Very high probability current control(s) will identify failure mode	2
Almost certain	Current control(s) relatively sure to recognize the failure mode.	1

If all factors are equally important, stated formula can be changed as follows:

$$\tau_i(k) = \frac{1}{3}\sum_{k=1}^{3} \Delta_i(k) \quad (7)$$

Step7: Prioritize the Failure Mode

The relational series are established based on the "Degree of Relation" between comparative series and standard series. The Degree of Relation closer to 1 means the failure mode is closer to the optimal value. The failure mode which has the lowest degree of relation should be the first one to improve. Therefore the lower degree of relation represents the higher risk priority.

IV. CASE STUDY

The camshaft is the principle working piece of the engine must incorporate cam lobes, bearing journals, and a gear is to drive the fuel inlet and outlet valve. The camshaft is likewise controlling the valve train operation of the engine. The camshaft is alongside the crankshaft it decides the firing order of engine cylinder.

We consider 4-cylinder camshaft sub assembly process as a case study. The figure 2 show the assembly of parts which is assembled in camshaft. There are six parts camshaft, woodruff key, thrust plate, gear, washer and bolt flange. All these parts assembled with standard operating procedure (SOP). All parts have different ID and manufactured in different-different industry but camshaft is manufactured and assembled in same company where we take data as a case study.

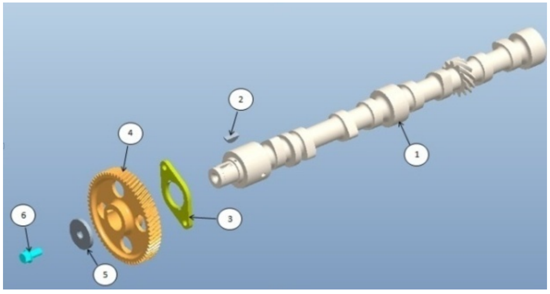

Figure 1: Parts of camshaft

Contextual analysis is directed and PFMEA procedure is applied to the sub assembly of camshaft. There are different task and procedures completed by different machine for collecting failure data. After acquired failure information PFMEA table has prepared. At long last, S, O and D calculated by using table 1, 2 and 3 respectively and PFMEA worksheet has created which is shown in Appendix-I. The RPN value for the failure modes was calculated by equation 1 and finally GRA approach result shown in table 4.

V. RESULT AND DISCUSSIONS

Appendix-I shows the result of PFMEA of sub-assembly of camshaft. From figure 1, it can be seen that sub assembly process of camshaft consist of total six operations and seventeen risk factors. The key fitment missing potential failure is process failure. This results in abnormal noise during engine testing. The conventional PFMEA RPN is 128 and their rank is 1 but in the case of GRA approach rank is 2. The rank of risk no.2 is fifth by the grey theory, while it is fifth by the conventional RPN. Meanwhile, the rank of risk no. 6 is 1 by the grey theory, while it is 2 by conventional RPN. As can be seen from Table 2, risk no. 6 is apparently the failure mode with the maximum overall risk and should be given the top priority, followed by risk no. 2, risk no. 9 and 11, risk no. 15 and 17, risk no. 2 and 12, risk no. 13 and so on grey theory.

Table 4; Conventional RPN and Grey RPN

OPN. No.	Process function	Requirement	Risk No.	Potential Failure Mode	Rank of Conventional RPN	Rank of Grey RPN
10	Load camshaft on woodruff key fitment fixture & Woodruff key fitment on camshaft.	Key fitment	1	Key missing	1	2
		Inclined fitment of key	2	Key not fitted inclined	5	5
20	Loading on cam gear pressing machine & Thrust plate mounting.	Thrust plate	3	Thrust plate missing	8	8
30	Fitment of cam gear on camshaft by pressing machine	Cam gear fitment	4	Cam gear miss	11	10
			5	Cam gear orientation wrong	13	13
40	Fitment of washer on cam gear	Washer fitment	6	Washer miss	2	1
50	Tightening the bolt with washer on cam gear	Tightening of bolt to 4~6 kgf-m	7	Bolt miss	7	7
			8	Inclined fitment of bolt in mounting thread of cam shaft	10	9
			9	Gun setting low value	3	3
			10	Operator tightens the bolt but did not torque it.	7	7
			11	Operator missed the operation of tightening the bolt.	3	3
			12	Torque wrench torque less	5	5
			13	Gun setting higher value	6	6
			14	Torque wrench torque more	12	12
60	Unloading of camshaft on storage trolley.	No dent on gears	15	Dent on gears	4	4
		No dent on cam shaft journals	16	Dent on cam shaft journals	9	10
		No dent on cam shaft lobes	17	Dent on cam shaft lobes	4	4

VI. CONCLUSION

PFMEA is an essential unwavering quality investigation method which has been generally utilized as a part of numerous industries. By and large, it is hard to secure exact failure data on failure risk, for example, severity, occurrence and detection. Hence, this paper proposed a grey PFMEA method that allows the risk factors and their relative weights to be evaluated in a linguistic manner rather than in a precise way for sub assembly of camshaft. In this connection, grey theory can be applied in PFMEA, and the results are almost the same. Compared with the grey theory in PFMEA can reflect the nature of relative ranking, because the ranking is based on the grey relational coefficient which is determined by the comparison between comparative and standard series. Grey relational analysis can be considered as a measurement of the absolute value of risk levels. If the evaluating information is incomplete or not reliable, grey theory PFMEA is still fit for this situation for the ranking.

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Appendix-I

Process Failure Mode Effect & Analysis (PFMEA)

Part No. & Name: Sub-assembly of camshaft	Team member:	Document No:
Customer-		Date:
Drawing No-		

OPN. No.	Process function	Requirement	Risk No.	Potential Failure Mode	Potential Effect (s) of Failure	Severity (S)	Potential Cause	e (O)	Current process control: Preventive	Current process control: Detective	Detection (D)	RPN	Rank
		Key fitment	**1**	Key missing	Abnormal Noise during testing & required rework of defective engine	8	Operator missed the operation of woodruff key fitment on cam shaft	2	SOP	Engine Testing	8	128	I
10	Load camshaft on woodruff key fitment fixture & Woodruff key fitment on camshaft.	Inclined fitment of key	**2**	Key not fitted inclined	Gear fitment difficult & gear gets incompletely fitted resulting in rectification of defective assembly	3	Operator unaware of correct assembly procedure	4	SOP	During press fitment of cam gear on cam shaft	6	72	V
20	Loading on cam gear pressing machine & Thrust plate mounting.	Thrust plate	**3**	Thrust plate missing	Fitment of cam shaft on engine not possible & no bearing effect for cam shaft & required rectification of defective	5	Operator missed the operation of thrust plate fitment on cam shaft	2	SOP	During assembly of cam shaft on engine	4	40	VIII

			4	Cam gear miss	Fitment of cam shaft on engine not possible & required rectification of defective assembly	3	Operator missed the operation of cam gear fitment on cam shaft	2	SOP	During assembly of cam shaft on engine	4	24	XI
30	Fitment of cam gear on camshaft by pressing machine	Cam gear fitment	**5**	Cam gear orientation wrong	Gear timing setting not possible & required rework of defective assembly	5	Operator mistakenly assembled gear in wrong orientation / unaware of correct assembly procedure	1	SOP & Poka-yoke for detecting correct orientation of gear before assembly	While gear timing	4	20	XIII
40	Fitment of washer on cam gear	Washer fitment	**6**	Washer miss	Distribution of pressure not evenly on cam gear	3	Operator missed the operation of washer fitment	5	SOP	Visually	8	120	II
			7	Bolt miss	T.G. Case damage due to cam gear came out during testing & required rework of defective engine	6	Operator missed the operation of mounting nut fitment on cam gear	1	SOP & Poka-yoke for de-clamping the cam shaft after torquing of mounting bolt on cam gear	Engine Testing	8	48	VII
			8	Inclined fitment of bolt in mounting thread of cam shaft	Mounting thread of cam shaft damage & required part to be reworked	5	Operator didn't hand tightened 2~3 of mounting bolts in the mounting threads of cam shaft	2	SOP	During fitment of bolt on cam gear	3	30	X
			9			6	Gun setting to low value	2	Calibration of gun once in month & 100% torquing with feedback limiter	Engine Testing Torque Audit	8	96	III
50	Tightening the bolt with washer on cam gear	Tightening of bolt to 4~6 kgf-m	**10**	Bolt torque less	T.G. Case damage due to cam gear came out during testing & required rework of defective engine	6	Operator tightened the bolt but did not torque it.	1	SOP & 100% torquing with feedback limiter	Engine Testing Torque Audit	8	48	VII

			11			6	Operator missed the operation of tightening the bolt	2	SOP	Engine Testing Torque Audit	8	96	III
			12			6	Torque wrench torque less	2	Lock type limiter provided on station	Engine Testing Torque Audit	6	72	V
			13	Bolt torque more	Mounting bolt break inside the mounting thread of cam shaft & part required to be scrapped	7	Gun setting to higher value	3	NIL	During fitment of bolt on cam shaft	3	63	VI
			14			7	Torque wrench torque more	1	SOP & 100% torquing with feedback limiter	During fitment of bolt on cam shaft	3	21	XII
60	Unloading of camshaft on storage trolley.	No dent on gears	**15**	Dent on gears	Abnormal Noise during testing & required rework of defective engine	5	Improper storage	2	Proper storage trolley to be provided to avoid contact of gears with each other after assembly.	Engine Testing	8	80	IV
		No dent on cam shaft journals	**16**	Dent on cam shaft journals	Fitment of cam shaft in its mounting hole in block not possible / cam shaft rotation jam after fitment & required part to be scrapped	3	Improper storage	4	Storage trolley with separation	During insertion / after fitment of cam shaft in block	3	36	IX
		No dent on cam shaft lobes	**17**	Dent on cam shaft lobes	Abnormal Noise during testing & required rework of defective engine	5	Improper storage	2	Storage trolley with separation	Engine Testing	8	80	IV