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A novel DFMEA Model for High Power Diesel Engine Design

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***Abstract* - As the design of diesel engine is the complex and challenging process, the structured system based design methodology to be followed for the design of high power diesel engine. In order to eliminate the premature failure and ensure the targeted specifications or performance, various design tools like QFD, DFMEA, bench marking, etc, are being adapted during the design phase. A research work was proposed to use DFMEA tool for the design high power diesel engine. In this approach a product modeling of sub system and parts are configured to list the major failure modes, effects of failures, and elimination methods in the design phase and effectiveness of analysis was improved by the structured and inter linked model.**

Key words: Design methodology,design tools, product modeling, DFMEA

I INTRODUCTION

In order to meet the demand for prime mover of higher capacity off highway equipment, a development proposal for 1200 hp engine was envisaged. Based on the existing 550hp engine, the new engine's design features are framed. The proposed system will have the advanced technologies, including the electronically-controlled, high-pressure fuel injection pump, high-efficiency turbocharger, air-cooling after cooler, etc.

Now s days, all original equipment manufacturers are insisting to introduce their products faster and with less cost [1]. Hence it is required to adapt various tools and techniques during the design phase to avoid failures after development. The commonly used tools in new product development process are quality function deployment(QFD), design failure mode effect analysis (DFMEA), design for 'X'(DFX), etc. As the design and development of diesel engine is the complex process, enlisting failure modes and its effects is a challenging task. Hence a structured novel approach to adapt DFMEA was proposed to design high power diesel engine for the off highway equipments. This paper describes the adaptation of DFMEA technique in development stage to improve reliability of the system and to avoid premature failure or failure after development.[2-3]

II PROBLEM DEFINITION AND DESCRIPTION

A. System definition by benchmark studies

DFMEA are being widely used in design of various parts of automobile [4]. Heavy duty diesel engines are extensively complicated in nature due to high combustion pressure, temperature and its operating profile or characteristics. Hence, heavy duty diesel engine was defined as system which converts chemical energy into mechanical energy. Further, itwas divided into major sub system like cylinder block system, main revolution system, intake and exhaust system, fuel injection system, cooling system, valve train systemand electrical system and its operating profile was defined [5].

The main system (engine) configuration or specification was defined based on the bench mark study as given in the table 1. The benchmark study was conducted collecting specification data from the various engine manufacturer of same class of engine. The major specification parameters are compared and best possible specification was finalized. During the compilation process the best possible use of existing engine parts in the new development was also explored to avoid the development of new parts. Hence the deviation from the proven design was avoided.

Table.1. System definition by benchmark study

Specification parameter		Competitor 1	Competitor 2	Competitor 3	Competitor4	Targeted specification
Engine Speed	RPM	2000	2100	2100	1900	2000
Gross Power	hp	787	760	1200	1200	1200
Net Power	hp	740	700		1178	1178
No Cylinders		12	12	12	12	12
Bore	in	5.4	5.11	5.51	5.51	5.51
Stroke	in	6	5.91	6.5	6.5	6.5
Displacement	in^3	1649	1,464	1861	1861	1861
Power Density	Hp/Lit	29.15	31.67	39.34	39.34	39.34
Emission		Euro II	Euro II	Euro II	Euro II	Euro II

B. Subsystem definition

The sub system performance parameters and functions are defined deliberately based on the system requirements. The design parameter values were defined to carry out design analysis, simulation and refinement of part definition [6]. After the definition of system and subsystem characteristics and functions, various failure modes and effects of failure on performance and functions of the subsystem parts were analyzed and solution method to eliminate such a failures were suggested. As the DFMEA was conducted in structured approach by the definition of system and subsystem during design phase the reliability and performance of the product could be improved significantly [7].

C. DFMEA model definition

The DFMEA model was developed based the organization of various parameters which could affect the performance and function of the product. The model was formulated as shown the figure 1. The failure model was defined from the base history of failure data collected for the similar family of engine in the fields where the equipmentare working. The history data collected were grouped based on the failure factors and was networked with failure results to define failure model. The possible failures enlisted were based on the failures which were caused due to quality deviations, improper operation, poor maintenance and terrain operating conditions, unexpected and unpredictable failures before optimization.

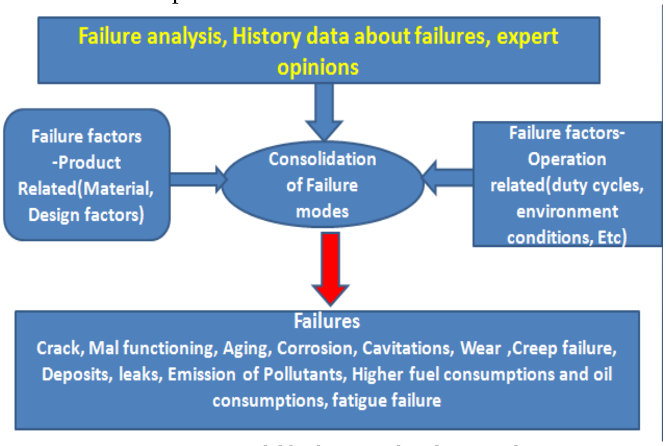

Figure.1. DFMEA model high power diesel engine design

II. RESEARCH AND METHODOLOGY

Now a days, major automobile and automobile parts manufacturers are using FMEA for their products and are not being used in full-fledged in off highway application due to the complicated failures modes and causes. DFMEA based approach was chosen to analyze the failure modes and its effects of the diesel engine used in off highway applicationfor the reliability and performance improvement [8]. The following are detailed description of the activities carried out to perform the DFMEA analysis for the design of heavy duty diesel engine.

A. Source of Data for analysis

The major potential failure modes of the engine will consist of four anti-functions such as partial function, intermittent function, no-function and unintended function [9-10]. These failures will be analyzed based the power and speed deviation from the specification, cooling, fuel injection, lubrication, electrical and auxiliary system failures.The source of data for the DFMEA was collected from earlier field failure report and from the expert opinions of various engineering functional teams.

B. Step by step procedure for structured DFMEA ofhigh power diesel engine system

The activities of DFMEA process were linked into various subsystems andanalysis was done for the all parts in the sub system.The failure modes and effects of failure were collected from various functional teams by brain storm process and by expert opinion poll. The following step by step procedure was followed in the DFMEA process.

C. System/ product specification, design and finalization engine block diagram

The aim of this activity was to describe the engine and its function. An understanding of the engine functions and performance are important to have clear idea about the product. This understanding simplifies the process of analysis and identification of sub systems/ parts that fail without performing the intended function. The block construction of the engine system gave the clear information about subsystem and the inference about the subsystem functions.

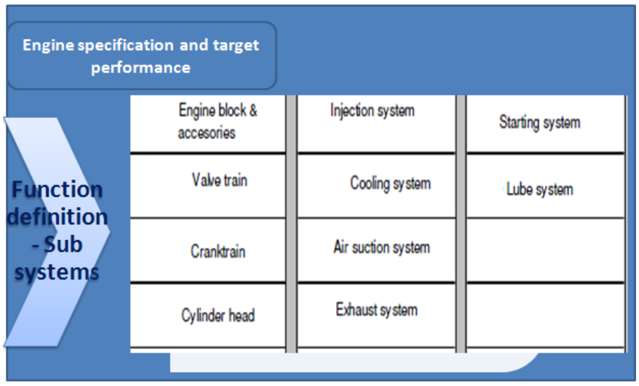

Figure.2 High power diesel engine block diagram

D.Brainstorm / expert opinion about potential failure modes

A failure mode is defined as the manner in which a component, subsystem, system, etc. could potentially fail to meet the design intent. This information was collected from the history data from the service department. The major failure occurred on the base engine was blow by, dust entry in turbocharger due to failure of pre-cleaner, valve drop failure and wear failure of valve train parts. Failure data were analyzed for the frequency of failure, hours of operation of engine in field, load utilized during the operation, operating cycle and duty cycle information. Refinement of potential failures of each parts and subsystems were completed with the discussion of cross functional team.

E. Listing potential effects of failure

For each failure mode identified the effectswere listed. A failure effectsare defined as the result of a failure mode on the function of the engine. This is failure to do the indented functions. Major effects of the failure are crack or mechanical failure of parts, leakages, wear, high oil consumption, high fuel consumptions, higher pollutants emissions, lower torque during operation, failure to meet the performance and other reliability issues.

F. Assigning severity rankings

A common industry standard scale uses 1 to represent no effect and 10 to indicate very severe with failure affecting system operation and safety without warning. The intent of the ranking is to determine whether a failure would be a minor nuisance or a major damage to the customer. This enables to prioritize the failures and address the real big issues first. The severity rankings are given in the table.2

Table.2. Severity rankings

PROBABILITY of Failure	Failure Probability	Ranking
Very High: Failure is almost inevitable	>1 in 2	10
	1 in 3	9
High: Repeated failures	1 in 8	8
	1 in 20	7
Moderate: Occasional failures	1 in 80	6
	1 in 400	5
	1 in 2,000	4
Low: Relatively few failures	1 in 15,000	3
	1 in 150,000	2
Remote: Failure is unlikely	<1 in 1,500,000	1

G. Assigning occurrence rankings

A numerical weight was assigned to each cause that indicates how likely that cause was. A common industry standard scale uses 1 to represent not likely and 10 to indicate inevitable. Occurrence of failures for engines parts were collected from the field failure data. In most of the higher power engines, failures were occurred due to deviation in operating profile and failure in cooling in intake system. In some cases, it was observed that the failure was happened due to poor maintenance of air intake system. Hence, the ranking of occurrence was done by formulating guidelines based on the frequency of failures happened for the same family of parts.

H. Assigning detection ratings

Detection is an assessment of the likelihood that the Current Controls (design and process) will detect the Cause of the Failure Mode or the Failure Mode itself, thus preventing it from reaching the Customer. The existing test protocol associated with each part and subsystems were considered for assigning the detection rating.

I. Calculation of RPNs

The Risk Priority Number is a mathematical product of the numerical Severity, Probability, and Detection ratings:
RPN = (Severity) x (Probability) x (Detection)
The RPN was used to prioritize items that require additional quality planning or action.

J. Developing the action plan

This activity wasthe determination Recommended Action(s) to address the potential failures that had a high RPN. These actions could include specific inspection, testing or quality procedures, selection of different components or materials, de-rating, limiting environmental stresses or operating range, redesign of the item to avoid the failure mode, etc.

K. Implementing the system/sub system/ components design

Analysis of the failure, its modes and effects was suitably ranked by expert opinions and reviews and was implemented into design.

L. Review for the improvements

After the above actions, re-assessment of the severity, probability and detection was done and the revised RPN's were calculated and system was refined.

III. RESULTS AND IMPLICATIONS

DFMEA was done based on the guidelines explainedabove and the results of each subsystem parts are given in table .3.

Table.3. DFMEA of Diesel Engine

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Severity	Potential Cause(s)/ Mechanism(s) of Failure	Probability	Design Controls	Detection	RPN
Cylinder Block								
Cylinder Block	Fracture	Engine Failure	10	Cyclic gas forces	1	Design for over load	2	20
Main bearing bolts	Distortion	Engine Failure	10	Over torque	0.5	Design for over load	1	5
Main bearing caps	HCF fracture	Engine damage	10	Mechanical load	1	Design for over load	2	20
Water jacket	Cavitations	Coolant loss	5	Over Temperature/ pressure	1	Higher thermal loading material	2	10
Water jacket	Cavitations	Coolant loss	5	Vibration	1	Fatigue loading	1	5
Water jacket	Leakage	Coolant loss inside and outside	5	Thermo-mechanical load	1	Cyclic load	2	10
Water jacket	Corrosion /scaling	Reduced cooling	2	Use of water without additives	1.5	Selection of suitable additives	2	6
Liner	Wear	Blowby	2	Thermo-mechanical load	1.5	Lubrication control	2	6
Liner	Polishing, seizure	Blowby	10	Ring sticking, depositions	1	Lubrication control	2	20
Gear train								
All gears	Fracture	Engine damage	10	Mechanical load	1	Design for over load	2	20
All gears	Wear	Increased backlash	2	Mechanical load	1	Tolerance contro	2	4

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All gears	Pitting, material outbreaks	Noise	10	Mechanical load	1	Backlash control	2	20
Cranktrain								
Crankshaft	Fracture	Crankshaft failure	10	mechanical load /thermal load	1	Design for fatigue loading	2	20
Main bearing	Wear/seizure	Scuffing	10	Mechanical load	1	Oil film control	2	20
Connecting rod bearing	Wear	clearances	2	Particles in oil	1.5	operation	2	6
Thrust bearing	Wear	Bearing damage	10	Axial load	1	Axial clearance	2	20
Torsional vibration	Crack	Increased vibrations	2	Mechanical load	1	Tortional vibration parts control	2	4
Flywheel	Functional failure	disturbed power	10	Inertia load	0.5	Inertia load	2	10
Connecting rod	Crack	Engine Failure	10	full load, overspeed	1	Selection of suitable cross section	2	20
Piston	Fracture	Blowby, scuffing, engine damage	10	Thermal and mechanical load	1	Full load and rated power operation	2	20
Piston	Wear	Blowby increase	2	Friction and carbon deposits	1	Ring pack design	2	4
Piston	Seizure	Engine damage	10	Lubrication	1	Lubrication control	2	20
Piston	Carbon deposition	Bore polishing	2	Lubrication	1	Lubrication control	2	4
Piston	Deposition	Ring sticking, seizure	10	Condensation	1	Lubrication control	2	20
Rings	Wear	Increase of blowby	2	Mechanical load	1	Lubrication control	2	4
Rings	Breakage	Seizure, pin sticking,	10	Mechanical load	1	Operation control	2	20
Piston Pin	Wear	engine damage	10	Mechanical load	1	Operation	2	20

						control		
Cylinder head								
Cylinder head casting	Fracture	Coolant into combustion chamber	10	Cyclic gas forces	0.5	Operation control	2	10
Cylinder head gasket	Leakage	Combustion gas leakage	5	Thermo-mechanical load	1	Contact stress	2	10
Valve seat	Wear	Performance deterioration	2	Mechanical/ thermal load	1	Profile control	2	4
Valve seat	Loosening	Engine damage	10	Thermal expansion, shrink fit	0.5	Profile control	2	10
Injection system								
Injector	wear	Irregular combustion	1	water in fuel	1.5	filter system	2	3
Injector	wear	Irregular combustion	1	dirt in fuel	1.5	filter system	2	3
Injector	deposits	service	1	combustion	1	Design for service	2	2
Injector	black smoke	Performance loss,restricted spray flow direction	2	combustion process	1	Injector hole design	2	4
Injector	loosening	performance loss	5	Engine Vibration	1	Clamping load	2	10
High pressure pump	Wear	leakage / failure of the pump	2	Lubrication	1.5	Selection of pump parameter	2	6
HP Lines and fittings	Crack	Fuel leakage to ambient / engine stop	10	Mechanical load	1.5	Pipe design	2	30
Rail pressure sensor	Fracture	fuel leakage to ambient	10	Vibration	1	Sensor mount design	2	20
Engine cooling system								
Water pump	Leakage	Coolant loss	2	Cooling load	1	Water seal selection	2	4
Water pump	Seizure	Failure	10	Engine load	1	Pump performance	2	20
Water pump	Cavitations	Reduced coolant flow	2	Coolant temperature	1	Full load operation	2	4
Sump	Leakage	Coolant loss	2	Vibration	1	Stiffener	2	4

						design		
Thermostat	Failure to open	Overheating	2	Failed wax element	1	Selection of thermostat	2	4
Valve train								
Camshaft	Wear	Loss of performance	2	Mechanical load	1	CAM lobe case hardening	2	4
Camshaft	Seizure	Engine damage	10	Poor lubrication	1	Lubrication control	2	20
Camshaft	Wear	Increased friction	2	Mechanical load	1	Lubrication control	2	4
Camshaft	Seizure	Engine failure	10	Poor lubrication	1	Lubrication control	2	20
Camshaft bearing bush	Crack	Engine damage	10	high load	1.5	material Selection	2	30
Push rod and cam follower	Wear	Loss of performance	2	Mechanical load	1	Tappet design and analysis	2	4
Push rod and cam follower	Seizure	Engine damage	10	Poor lubrication	1	Layout design	2	20
Pushrod	bending	Engine damage	10	load/length ratio	1	Layout design	2	20
Rocker arm	Wear	Loss of performance	2	Mechanical load	1	Rocker ratio	2	4
Rocker arm	Seizure	Engine damage	10	Poor lubrication	1	Lubrication control	2	20
Springs	Valve drop	Engine damage	10	Cotter position	0.5	Selection of springs	2	10
Valve	Wear	Engine damage	10	valve drop	1	Design for thermal load	2	20
Exhaust system								
Turbine housing	Wear	TC-damage	5	Thermal - mechanical load	1	Exhaust flow control	2	10
Compressor wheel	Erosion	TC damage, loss of power	2	Dust - fine particles	1.5	Process control	2	6
Exhaust Gasket	Wear	Exhaust gas leakage to	2	Wear	1	material Selection	2	4
TC oil supply and return pipes	Crack	Poor oil supply	2	Thermal-mechanical load	1	Full load operation	2	4
Exhaust manifold	Crack	Over heat	2	Thermal-mechanical load	1	Design thermal and cyclic loading	2	4

It is evident from the DFMEA that the RPN is very high for high pressure lines and fittings and cam bearing bush. It's failures modes and causes are crack and mechanical loading. Hence while designing such a component, sufficient design factors to be considered to withstand cyclic load and proper lubrication.

Similarly the RPN is high for the parts cylinder block, main bearing caps, liner, gears, crank shaft, main bearing, thrust bearing, piston, piston rings, piston pin, sensors, water pump, cam shaft, push rod, rocker arm and valves. Hence the above parts to be designed after completion of design analysis for heavy cyclic loading, fatigue loading, proper lubrication, combustion or peak firing pressure and inertia forces.

The RPN values were used for calculating the sensitivity index of failure for every part of engine and were given the table.4. The sensitivity of failure was measured in the scale 1 to 5, where the value 5 represents the higher sensitivity of failure and 1 represents the least sensitivity of failure. The engine parts were classified into various groups based on the failure sensitivity analysis and suitable design solution was assigned to avoid such a failure after the development of engine.

Table.4. ComponentSensitivity for failure

Engine Parts	RPN	Sensitivity for failure
HP Lines and fittings, Camshaft bearing bush	30	5
Cylinder Block, Main bearing caps, Liner , gears,Crankshaft, Main bearing,Thrust bearing ,connecting rod ,Piston,Piston Pin,Rail pressure sensor,Water pump,Camshaft ,Push rod and cam follower,Pushrod , Rocker arm ,Valve ,Water jacket ,Flywheel ,Cylinder head casting , Cylinder head gasket , Valve seat , Injector ,Springs ,Turbine housing	20	4
Liner , Connecting rod bearing ,High pressure pump,Compressor wheel ,Main bearing bolts	6	3
Torsional vibration,Piston, Rings , Valve seat ,Injector ,Water pump, Oil Sump,Thermostat ,Camshaft ,Push rod and cam follower,Rocker arm ,Exhaust Gasket,TC oil supply and return pipes ,Exhaust manifold	4	2
Injector	3	1

Hence by the above analysis, it is evident that failures of engine parts can be eliminated after the development and will give the detailed procedure to be followed during operation and maintenance. The DFMEA is effective tool that will help the product to be in healthier condition in all stages of the product life cycle.

IV. CONCLUSION

The Design FMEA is a disciplined analysis for the new product development with the intent to correct or prevent the design-based failure prior to proto development or production regularization. Hence for the design and development of 1200Hpdiesel engine, DFMEA based approach was suggested to help to reduce the failures during the design phase and to finalize the logical design process. It will also provide means for continuous product improvement.

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