Design for Six Sigma in product development at Ford Motor Company in a case study on robust exhaust manifold design

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Abstract: Many Design for Six Sigma approaches used throughout the industry have one critical aspect, which is the linkage between the phases of the product development process and ultimately how effectively design decisions can be influenced. Presenting a case study on robust design of exhaust manifolds, we show how transfer function knowledge is used to ensure less iterations than previously needed, satisfy program timing needs and systematically generate a robust solution. This case study uses a parametric model for Computational Fluid Dynamics (CFD) and experimental design techniques especially suitable for computer model responses. Meta-modelling is, in this case, the measure against resource-intensive Computer-Aided Engineering (CAE) applications. Analysing the range of all packageable alternatives, rather than just nominal parameters, allows for the assessment of robustness under the presence of noise factors, such as dimensional part-to-part variation. The outcome is a new approach in the manifold design.

Keywords: Design for Six Sigma; Six Sigma; Ford Motor Company; product design; robust design; exhaust manifold; meta-modelling; noise factor; transfer function; Computational Fluid Dynamics (CFD).

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David Lloyd-Thomas works in Inline Gasoline Engine Engineering at Ford Motor Company where he supervises a CAE Team working on engine performance and internal gas flows in the powertrain. Before joining Ford he worked for ArvinMeritor, as a CAE Supervisor working on exhaust systems. Before that he worked at Harwell Laboratory, part of the United Kingdom Atomic Energy Authority. He received his Masters in Engineering after studying at Emmanuel College, Cambridge University. He has written several technical papers on automotive applications of computational fluid dynamics and on composite materials.

Faysal Khalaf has been contributing to Ford Motor Company since 1995. He holds a PhD in Industrial Engineering, a Master's degree in Manufacturing and a Bachelor's degree in Mechanical Engineering. Currently, he is leading global deployment and integration of DFSS at Ford Motor Company. He has led and coached numerous DFSS/DMAIC projects. He is also leading development and training of DFSS training modules and deploying DFSS integration in product development at Ford Motor Company. He holds the position of Global/Corporate Design for Six Sigma Manager and is a recognised DFSS expert at Ford Motor Company.

1 Introduction

Design for Six Sigma naturally relies on availability of advanced modelling, simulation and analytical verification techniques to accomplish early decision making in the design and engineering of new products. This is true during the technology and concept selection phases as well as after implementation readiness. The creation of Computer-Aided Engineering (CAE) interfaces with project teams is a key enabler. Ford Motor Company approaches this need from two sides. Firstly, the corporate-wide "Analytical Reliability & Robustness" tools enable project teams to use advanced optimisation and robustness assessment techniques. Secondly, the functional and corporate Design for Six Sigma champions recognise the need for advanced modelling tools and ensure that they are provided in the characterisation phase of typical projects.

2 Minimisation of late design changes

The case study in this paper is presented, as an exhaust manifold design was in the past a particularly problematic area with respect to the program timing needs. Usually, thermal durability issues were discovered late during hardware verification testing, as gas flow requirements dominated design geometry and package decisions. The lack of analytical verification for all relevant response metrics *simultaneously and early* in

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program timing used to cause enormous testing expenditures, yet, still only yielding suboptimal fixes to thermal durability issues, as the countermeasures to these came (in the absence of major redesign alternatives) often from material upgrades or other higher cost alternatives.

3 Approach

Design for Six Sigma focuses on a disciplined implementation of well-developed statistical and engineering decision tools by managing their integration into the product development. For the project phases and the corresponding phases of the product development, it particularly focuses on the following phases.

3.1 Definition phase

- consumer insight
- market research
- Kano modelling
- quality function deployment and
- target setting and verification.

Appropriate resource allocation, sensible scope and alignment with the product development timing are key for the definition phase. This can be formalised by calling the beginning of it the 'Mission' phase.

3.2 Characterisation phase

- concept generation and selection
- functional diagramming
- axiomatic design (avoiding unnecessary coupling of outputs)
- parameter diagramming, identifying input and output, controllable and uncontrollable factors (noise factors)
- transfer function development (deductively or inductively/with designed experiments) and
- Failure Mode and Effects Analysis.

A comprehensive input from product design activity is critical to quality of event in the definition and characterisation phase.

3.3 Optimisation phase

- parameter design
- tolerance design

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- multiobjective optimisation (including desirability or loss function formulation)
- sensitivity analysis (local/gradient-based and global/Monte Carlo-based) and
- analytical reliability and robustness (e.g. defects for a given distribution).

Aggressive timing in today's automotive engineering world demands increasing analytical (computer simulation-based) optimisation, as opposed to the traditional (inductive) hardware design of experiments and verification.

3.4 Verification phase

- reliability demonstration (being able to excite each failure mode with a noise factor, with optimised design successfully passing noise scenario)
- design verification, accomplishing reliability demonstration with program resources and
- control planning and launching of related DMAIC (downstream Six Sigma) projects.

Verification can best be achieved by combination of both analytical methods (e.g. Monte Carlo simulation, where applicable) and hardware testing methods with built-in noise factors (e.g. using a set of three samples with noise factors present, such as tail-testing with preworn components at the end of specification). Ideally, analytical methods would come first and hardware subsequently, so that the more resource-intensive hardware testing can be kept to a minimum and applied only to those designs that were successful in the previous stages of development.

4 Selecting Design for Six Sigma projects

Having emphasised that appropriate project scope is so critical for meaningful project definitions, it is important to define the three typical categories for Design for Six Sigma projects in the automotive industry with respect to constraints on design (Soderborg, 2004):

1 new product or product breakthrough
2 evolutionary change in the next generation product and
3 adjustment to the existing product design.

The first of these categories imposes the least constraints on design freedom and timing; the last category gives the heaviest constraints. The application example, which is the subject of this paper, is a case of evolutionary change in the next generation product.

In summary, a successful implementation of Design for Six Sigma ensures the following:

1 Project selection is aligned to key milestones of product development, taking timing and control level networks into account, which makes integration into the decision flow of larger organisations successful.

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2 Project selection is selective and customer focused to support product development in the key areas, when dealing with:
   a a new or unique technology
   b difficult failure modes and
   c design issues with existing products.

5 Useful elements of a Design for Six Sigma governance system

The documentation of projects and transfer functions is important to facilitate the accumulation of corporate knowledge. Usually, we find a relatively large number of carry-over subsystems and components in the next generation product, so often the programme team can reuse existing transfer functions and systematically assess performance in a new application environment. This is manageable, as long as:

- transfer functions are well documented, updated and do not need to be developed from scratch again and again
- new application noise factors are identified through high-integrity Failure Modes and Effects Analysis, including updated failure cause data and
- continuity with suppliers and contributions to Failure Modes and Effects Analysis is maintained.

Sustainable Design for Six Sigma implementation needs the integration of projects into the 'mainstream' decision-making process. Project databases must be:

- user-friendly and not overly burdensome to update/use
- linked to general product development (no 'island-solution' unconnected to other corporate systems) and
- equipped with powerful search functions, without need for special tools or front-ends.

Design for Six Sigma is about being result-driven rather than activity-driven. The changes due to Six Sigma projects are reflected in optimised design decisions and leaner verification, which means robustness to small sample sizes, timing and resource constraints and noise factors. Measuring performance by project activity or by application of specific tools is not results-driven and hence focuses too much on the occurrence of 'error states', which should be avoided.

6 Application of the case study

The aftertreatment system of a gasoline engine will typically consist of an exhaust manifold and catalytic converter assembly. The former has a major failure mode of thermal cracking caused by the heat flow through the manifold as it transports gas from the engine to the converter. The latter has a major failure mode when tailpipe emissions fail to meet the targets and this has been shown to be linked to the gas flow through the

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