Automatic shape variations for optimization and innovation

Shape Optimization of Cylinderhead Gasket using CFD

Noel Leon, Jose Cueva, Cesar Villarreal, Sergio Hutron, German Campero
Tecnologico de Monterrey, CIDYT-CIII
Ave. Eugenio Garza Sada # 2501
Col. Tecnológico, Monterrey, NL, CP. 64839, Mexico
http://cidyt.mty.itesm.mx

Abstract. This paper presents an innovative tool and method that allow efficient innovation of shape and topology of virtual parts at both mesh and CAD levels using optimization methods. The method consists of automatic variations of shapes in CAD/CAE environments that allow effective search for new shapes that are not considered initially by designers.

1 Introduction

Contemporary designers face the dilemma of doing design tasks in a context where the available tools and methods are not always adapted to satisfy design requirements that are increasingly more focused on potential creativity enhancement [1].

This paper addresses the main motivations of the industrial sector, regarding the engineering innovation activity with computer tools and methods. It is focused on the innovation of shape and topology using a proven and mature method that has been used successfully for parametric optimization. In addition the method extends its application to design automation and CAI for integrating these methods and tools into engineering processes.

It is known that, commonly, performance improvement is first obtained through quantitative changes in parametric design in search for optimization, but once the resulting improvement reaches its limit and further performance improvements are not possible, new searches must be carried on through qualitative changes or paradigm shifts that lead to innovation [2]. Optimization, then, is a search process that looks for the most advantageous state of equilibrium before a contradictory situation where the improvement of one or several performance characteristics, deteriorates others. In order to get out of this deceptive goal, innovative concepts are needed by changing not only parametric values, but also shapes, topologies and physical principles.

Currently available CAD and CAE systems were originally conceived for facilitating only parametric variations on modeled parts. Parametric modeling has simplified the design process because it allows easy modification of parts. In recent times, topology optimization methods have been also introduced in meshing environments to improve product performance [1, 2]. These topological optimization functions are currently used to find optimum topologies and shapes for given parts under prearranged conditions. This is achieved by describing a defined space for the part through a Finite Element (FE) mesh model while an optimization algorithm finds an optimal material distribution within a series of established restrictions. Properties of the FE model such as density or Young modulus are modified during the optimization process until an optimum shape is obtained [3, 4]. This type of mesh-level variations is practical for finding suggestions regarding part shapes and topologies, however shapes and topologies obtained this way are not models with a CAD structure, and they require manual post processing or even a complete redesign if it is desired to convert them into a full structured CAD model [5].

In this paper innovative tools and methods are presented that allow efficient optimization and innovation of shape and topology of virtual parts at both mesh and CAD levels.

In this work new advances are shown for implementing methods that may be integrated into conventional CAD/CAE systems for executing shape and topology changes that transcend parametric values while searching for performance enhancements with the aid of genetic algorithms and shape and topology variations at both CAD and mesh models that may be converted in both directions.

2 Splinization and Mesh Morphing

For the development of this method and its adaptation to the current CFD analysis methodologies the splinization approach presented in the past CAI Conference [6] needed to be translated into the CAE domain. This paper describes how the splinization concept was translated into the meshing software for integrating the shape variation method with the CAE analysis method.

Even though the main focus on the splinization technique is about shape variations that allow the persistence of CAD models, a new interesting way of obtaining these same advantages is being developed to allow special shape variations at mesh level and then be translated into direct modification for a previously “splinized” CAD feature. For this purpose mesh morphing in existing commercial finite element meshing software was used, which allow shape variations to be made to a mesh model without remeshing it. One further reason mesh morphing becomes advantageous in this context is because the interpolation of previous results can save a lot of computational time in CFD simulations. Since the changes in geometry are small compared to the size of the complete model, previously converged simulation result (or interpolated new result) can be used as an initial guess and speed up the simulation process. To take an advantage of converged solution, it is good to have a mesh model that remains consistent in its number of elements and elements' IDs.

Since any modification that requires remeshing would cause inconsistency in these matters, mesh morphing is a good option. In mesh morphing, a domain is an area where shape modification propagates to define their movements. The way the mesh surrounding the shape is modified depends on a bias value (so called a "handle") that is equivalent to the tension of a Bezier curve. Within each domain handles are defined.

Under these circumstances, a direct relation can be established between these morphing handles, and the position of the control points that define a spline. With this, a connection between the splinization approach and mesh morphing has been established. A morphing handle approach reduces the number of design variables while splinization increases degree of freedom in shape. The final goal is to integrate the CAD/mesh shape optimization process through splinization methodologies with finite element meshing software for CFD and structural simulations and genetic algorithms in an automatic manner.

2.1. Mesh morphing

As known from finite element method, a mesh is constituted of elements, which are constituted of nodes and edges connecting two nodes. Nodes are defined by coordinates in space which, by being strategically modified, can alter the entire mesh model. By displacing every set of node coordinates, the whole mesh model can be moved. In the same manner, it can be rotated, scaled and stretched in every way.

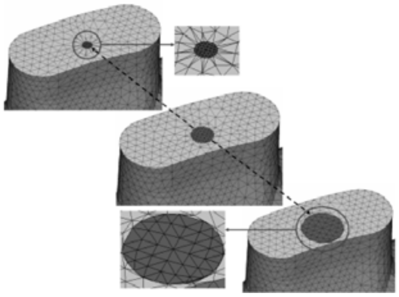

Fig. 1. Extensive morphing diminishes element quality.

Because it is sometimes desirable to modify only a certain feature within a mesh model, manipulating node coordinates must be done in a very controlled manner to maintain model consistency and quality of the mesh elements. In fact, the best way to modify a certain shape would be to alter the nodes defining it, and then smoothing the node displacements so that the perturbation of the elements is minimized and mesh topology is preserved. This effect is known as mesh morphing, which is a tool included in some meshing software.

For each modifiable shape, edge domains are formed in the shape that defines the mesh boundaries where morphing may be performed without significant deterioration of the mesh quality of the region. Several stepped regions allow defining a bigger region than would be allowed by mesh quality criteria when performing the variation in a big region. These stepped regions are placed along the curve of the edge domain that will be modified individually.

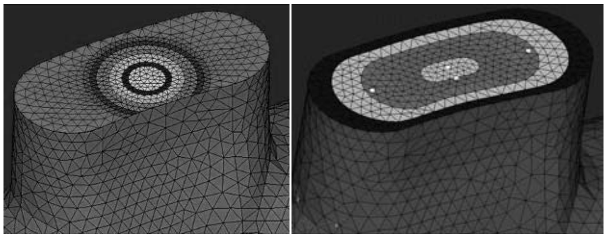

Fig. 2. Mesh constructed with proper pre defined morphing levels.

With this tool, a domain can be created to define a group of elements to be taken into account as a morphing unit. Within a domain, handles allow the actual node manipulation. Handles can define curvatures or approximate diameters in the case of circular domains; they can be also freely moved, anchored at a given point, assigned movement restrictions to, etc. Even though this kind of variations have major limitations because of mesh quality constraints, they are very practical when small changes in shapes need to be made.

3. Case Study: Shape Optimization of CylinderHead Gasket using CFD

The traditional process involves geometry, meshing tools and Computational Fluid Dynamics (CFD) simulations for the performance enhancement of the cooling water jacket of cylinder engines. This process has been usually performed manually modifying the gasket holes dimensions based on the results of CFD simulations subject to manufacturing, packaging and material constraints. However, this process is highly time consuming.

Water jacket is designed for peak power condition that is representative of the worst case scenario with respect to heat rejection to coolant with the flow rate specified at peak pump output.

For designing the water jacket, predominant design variables are number, dimension and location of each gasket hole. Gasket holes should reside inside of intersection of block and head water jackets.

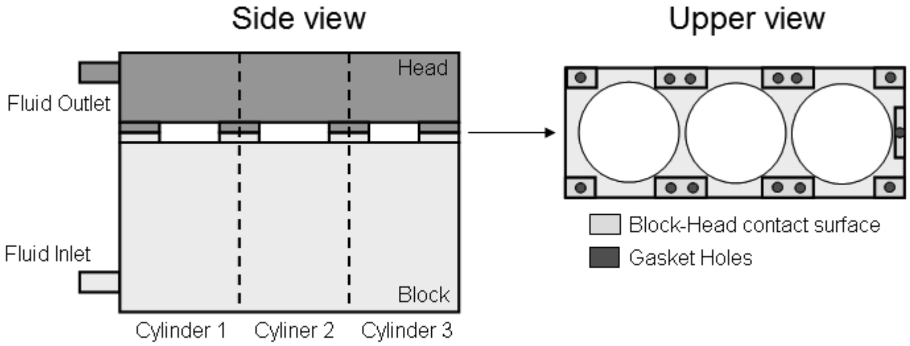

Fig. 3. Block and head water jackets intersection and gasket positioning.

Currently, design iterations take about 1/2 week for each change to do the mesh generation and run the analysis. The simulation time for each simulation using a 4CPU machine is about 16-20 hours. Under these conditions the possibilities of variations of shapes and topologies are very limited and therefore only changes of the holes diameters are commonly introduced.

The goal of applying shape optimization concepts and methods is to significantly reduce the time for finishing a design, by providing a functional modeling methodology that integrates the engineering concept and the geometry restricted to manufacturing, packaging and material constraints. Additionally performance increments beyond those achieved by traditional manual methods may be expected as not only changes in diameter values but also shape and topology variations

The design has to be performed under the restrictions coolant flow distribution around each cylinder, flow-distribution near critical areas such as exhaust valve bridge, spark plug and peak velocity zones that are prone to metal erosion. Thermal analyses are performed to predict heat transfer coefficients and for transferring the information to structural analysis. Thermal analyses provide the coolant flow rate from the water pump performance, heat fluxes corresponding to the peak power condition in different regions of the water jacket.

3.1 Optimization of the engine cooling process

Holes in a cylinder head gasket are the only available passage for cooling fluid between the cylinder head and cylinder block. The pattern of gasket holes defines the flow conditions within the water jacket that allows heat exchange from cylinder head and block to coolant. As shown in [7], changes in gasket holes pattern can positively impact heat transfer coefficients for the cylinders, thus improving engine cooling. In this case the objective of gasket holes optimization is to maximize the minimum area averaged heat transfer coefficient as well as to minimize the maximum difference among heat transfer coefficients among cylinders.

The overall process consists of software applications to run DOE, mesh update, CFD analysis, and Process integration for performance optimization.

With the help of the mesh morphing process explained earlier, in the DOE step re-meshing is avoided while boundary conditions are changed.

The optimization step uses mesh morphing to achieve a new mesh in a reasonable time. Overall procedure of DOE and optimization process of gasket holes is presented in Figure 4.

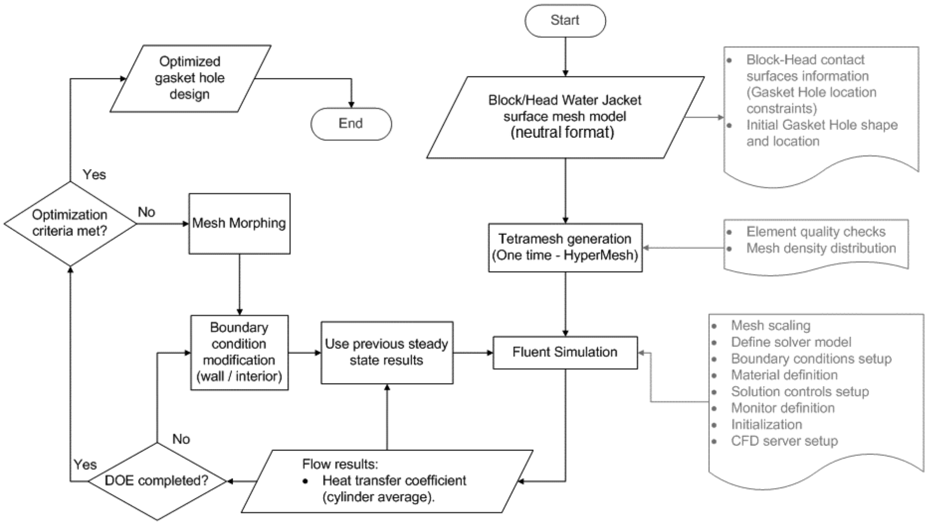

Fig. 4. Overall procedure of DOE and optimization process of gasket holes.

The main benefit of this process template is reduction of man-hours required for set-up and post processing by eliminating routine tasks that are now implemented automatically.

After this mesh-based shape modification technique reaches a final design; work would be still required in order to feed this final design back to the designers. The implemented procedure allows closing this shape optimization process by sharing of equally flexible parameterization techniques both in the CAD and CFD environment by feeding the shape variations of the mesh morphing controlled by the handles as shown in Figure. 5 to the CAD environment as control points of a spline where the final values of the morphing handles become the control points of the spline. Through this approach, the mesh-based shape optimization can be performed and then, when the optimal shape design has been defined, the final shapes can be automatically translated to the CAD design.

3.2 Preliminary results

At this point the investigation has been conducted in a simplified model shown in the Figure 6, in which six holes (shown in Figure 7) perform a scale factor, without shape and/or topology variations yet

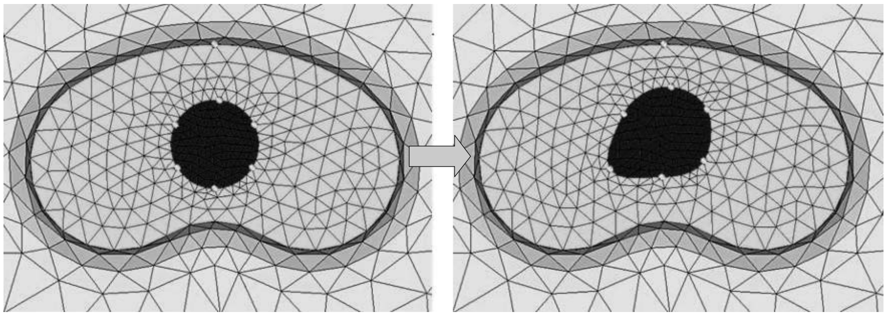

Fig. 5. Gasket hole modification with splines.

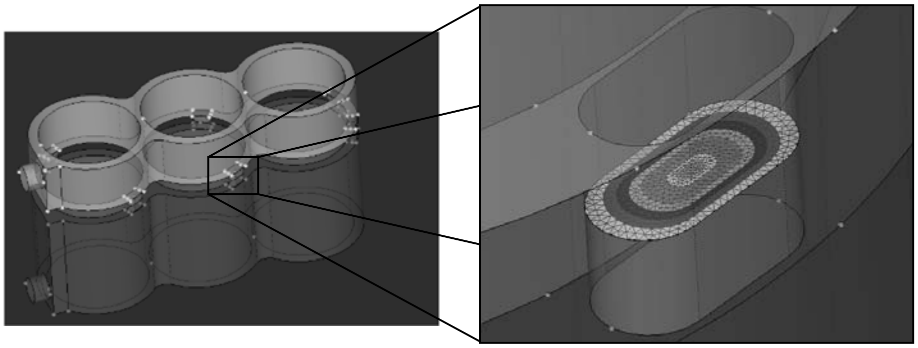

Fig. 6. Simplified model gasket holes.

The mesh dfined contains small elements (0.25 mm) where is necessary to be more precise for example holes and thin walls. Larger elements (up to 3 mm) are used in other areas. As boundary conditions an initial coolant temperature of 366°K was defined. The coolant properties were defined based on a common mixture of water and ethylenglicol (r=1028.5 and m=0.00072). The neighborhood cultivation algorithm was used with the criteria of maximum 400 iterations.

The process integration for performance optimization in the software applications has been already achieved. As mentioned in the previous chapter, process integration helps automate the mesh modification and CFD analysis. Therefore it is possible to perform a DOE and/or to conduct an optimization using a search algorithm such as a genetic algorithm.

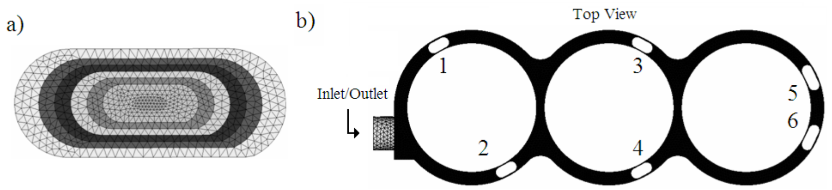

Fig. 7. a) Gasket hole mesh, b) Gasket holes positioning.

With the process integration a fractional factorial DOE analysis with four levels for each hole was performed. These hole levels are classified into a) fully opened; b) one third of the total area; c) two thirds of the total area; and d) completely closed.

As explained earlier, the objective is to maximize the minimum heat transfer coefficient (HTC) as well as to minimize the maximum difference of HTC among cylinders. To perform the DOE analysis the objective function to maximize is defined as follows: HTC sum of the three cylinders minus four times the sum of the differences among the cylinders. The results of the DOE analysis are shown in Table 1 and the Pareto frontier for visual approach of the optimization can be seen on the Figure 8.

Table 1. Fractional Factorial DOE analysis top ten HTC.

Rank	Gasket Hole Area (Percentage)						HTC Cylinders (W/m^2 K)	Differences between Cylinders (W/m^2 K)			Objective
	1	2	3	4	5	6	1+2+3	|1-2|	|2-3|	|3-1|	
1	1/3	0	0	1/3	1/3	1/3	271.9	28.2	8.9	19.2	103.0
2	0	1/3	1/3	0	1/3	1/3	269.4	28.0	9.2	18.8	101.4
3	0	0	1/3	1/3	1	1	233.9	24.3	0.0	24.3	88.1
4	1/3	1/3	0	2/3	2/3	2/3	246.3	26.4	1.5	24.9	88.0
5	1/3	1/3	2/3	0	2/3	2/3	246.5	27.9	2.1	25.7	79.2
6	0	0	1	1/3	2/3	2/3	238.2	20.2	6.3	26.5	79.0
7	0	0	1/3	1	2/3	2/3	222.6	17.9	9.9	27.7	56.2
8	2/3	0	1/3	2/3	2/3	1/3	244.1	27.0	5.1	32.1	51.6
9	1/3	1/3	2/3	2/3	1	1	233.1	25.5	5.0	30.5	50.1
10	0	2/3	2/3	1/3	1/3	1	234.2	28.3	2.9	31.2	47.1

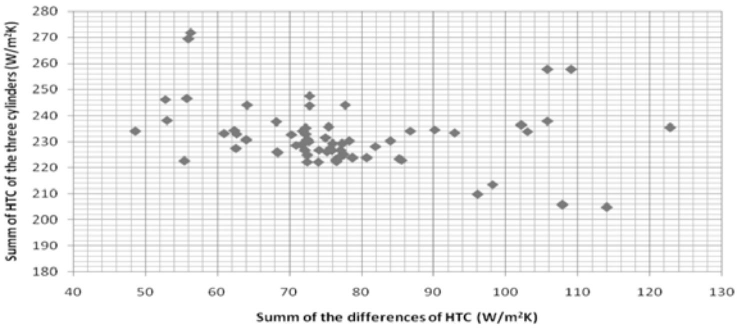

Fig. 8. Pareto frontier between the two objectives.

In these preliminary results, the tendency of having bigger holes while they are farther from the inlet is higher. Based on this fact, levels should be chosen for the gasket holes as a starting point so that optimum can be reached quickly.

4. Future work

Taking advantage of the automatic shape variation presented in this paper, it is proposed to apply this technique looking for innovative shapes of Savonius tye rotors for wind generators. The Savonius wind turbine was developed in the early 20's of last century and has been undermined because of its low efficiency in comparison with traditional wind turbines of horizontal axis. Later groups of investigators have worked finding new shapes of the Savonius rotor making subtle changes to its profile shape, but the traditional geometrical features such as arcs and lines have remain unchanged. By using splines in the rotors design it is possible to create forms never explored before, which may be analyzed trough the techniques described in this paper for the Shape Optimization of CylinderHead Gasket using CFD.

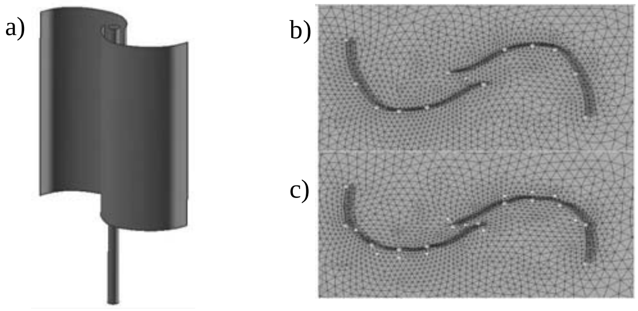

Fig. 9. a) Traditional Savonius rotor, b) original profile shape, b) modified profile shape using splines.

5. Conclusions

Computer Aided Innovation may benefits from mature optimization methods for performing shape and topologic variations in CAD/CAE environments leading to innovative shapes and topologies that allow achieving higher performance when parametric optimization faces technical contradictions. Using "splinization" techniques together with mesh morphing and genetic algorithms facilitates the search for higher performance exploring innovative shapes that avoid expensive manual trial and search methods.

6. Acknowledgments

The authors acknowledge the support received from Tecnológico de Monterrey through Grant number CAT043 to carry out the research reported in this paper. Authors acknowledge collaboration effort with Vamshi Korivi, Surendra Gaikwad and Su Cho working from Aerothermal Center of Competence and Product Development IT, Chrysler LLC.

References

1. Cavallucci D, Leon N, Towards "Inventiveness-Oriented" CAI Tools, Proceeding of IFIP 18th World Computer Congress, Topical Sessions, Building the Information Society; pp. 441-452, Toulouse, France , 22-27 August 2004.
2. Leon N, Gutierrez J, Martinez O, Castillo C, Optimization vs. Innovation in a CAE Environment, Towards a "Computer Aided Inventing" Environment. Proceeding of IFIP 18th World Computer Congress, Topical Sessions, Building the Information Society; pp. 487-495, Toulouse, France , 22-27 August 2004.
3. Pandley MD, and Sherbourne AN, Mechanic of shape Optimization in Plate Buckling, Journal of Engineering Mechanics, Vol. 118, No. 6, pp.1249-1266, June 1992.
4. Vicini A and Quaglierella D, Airfoil and wing design through hybrid optimization strategies, 16th Applied Aerodynamics Conference, American Institute of Aeronautics and Astronautics, 1998, AIA Paper 98-2729.
5. Binder T, Hougardy P, Haffner P, Optimierung von Guss- und Schmiedeteilen bei Audi, Audi AG, D-85045 Ingolstadt, Audi AG, D-74172 Neckarsulm, FEM, CFD, und MKS Simulation, 2/2003.
6. León Rovira, Noel; Silva Sierra, David Alejandro; Cuevas, José María; Gutierrez Hernández, Jorge César, Automatic Changes in Topology of Parts and Assemblies in 3D CAD systems. Proceeding of the 1st IFIP Working Conference on Computer Aided Innovation, Ulm, Germany pp: 96-107, November 2005.
7. Shih S, Itano E, Xin J, Kawamoto M and Maeda Y, Engine Knock Toughness Improvement Through Water Jacket Optimization, SAE paper 01-3259, SAE International, 2003.