Parallel Computational Fluid Dynamics
International Conference Parallel CFD 2002
Kyoto, Japan, 20-22 May 2002

EXHAUST MANIFOLD DESIGN FOR A CAR ENGINE BASED ON ENGINE CYCLE SIMULATION

Masahiro Kanazaki*, Masashi Morikawa†,

Shigeru Obayashi* and Kazuhiro Nakahashi†

*Institute of Fluid Dynamics, Tohoku University, Sendai 980-8577, Japan
email:kanazaki@mail.cc.tohoku.ac.jp, web page: http://www.reynolds.ifs.tohoku.ac.jp/edge/

†Dept. of Aeronautics and Space Engineering, Tohoku University, Sendai 980-8579, Japan

Key words: Intake/exhaust system, Empirical engine cycle simulation, Unsteady flow, DRMOGA.

Abstract. *Multiobjective design optimization system of exhaust manifold shapes for a car engine has been developed using Divided Range Multiobjective Genetic Algorithm (DRMOGA) to obtain more engine power as well as to achieve less environmental impact. The three-dimensional manifold shapes are evaluated by the unstructured, unsteady Euler code coupled with the empirical engine cycle simulation code. This automated design system using DRMOGA was confirmed to find Pareto solutions for the highly nonlinear problems.*

1 INTRODUCTION

To improve intake/exhaust system performance of a car engine, many design specifications are required. In addition, car engines today are required not only to have more engine power, but also to be more environmentally friendly. Exhaust gas should be kept in high temperature in the exhaust pipe especially at low rpm conditions because the catalyst located at the end of the exhaust pipe will absorb more pollutant in high temperature conditions. Exhaust gas should also be led from the piston chambers to the exhaust manifold smoothly to maximize the engine power especially at high rpm conditions. Such design usually has to be performed by trial and error through many experiments and analyses. Therefore, an automated design optimization is desired to reduce technical, schedule, and cost risks for new engine developments.

In the previous study, the exhaust manifolds for the high power engine (Figure 1) was assumed and the merging configurations of the exhaust manifold and pipe's radii (defined constantly along a manifold) were designed and focused on the interaction of the exhaust gas around junctions of the manifold [1]. The objective functions were to maximize the gas temperature at the end of the exhaust pipe at 1,500 rpm and to maximize the charging efficiency that indicates the engine power at 6,000 rpm. Many solutions achieved high engine power as well as to reduce the environmental impact.

While, according to the previous study, a larger radius of the manifold was effective to reduce the environmental impact, but such design candidates showed less engine power. In view of this result, this study will make the pipes' radii increased step-by step when pipes are merged, expecting further improvements in both objective functions. Such design is more realistic and known for the good performance of the exhaust manifold from experiences at industry. Objective functions considered here are the same as the previous study. Divided Range Multi-objective Genetic Algorithm (DRMOGA) was also employed [2].

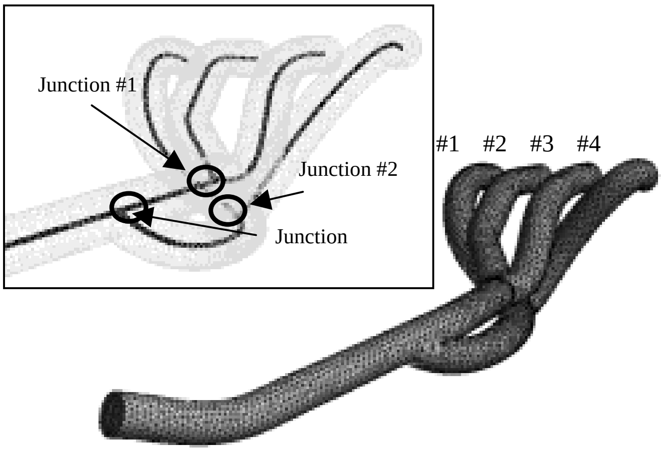

Figure1: The initial manifold shape and design variables as junction positions on pipe centerlines

2 FORMULATION OF THE OPTIMIZATION PROBLEM

2.1 Objective functions

The objective functions considered here are to maximize the gas temperature at the end of the exhaust pipe at 1,500 rpm and to maximize the charging efficiency at 6,000 rpm, where the charging efficiency indicates the engine power. These two objectives are function of a flow over an engine cycle. A flow field of a manifold shape is computed by solving an unsteady three-dimensional inviscid flow code [3]. Unsteady boundary conditions for a flow to and from a manifold are simultaneously computed by using the one-dimensional, empirical engine cycle simulation code [1, 4].

2.2 Divided Range Multiobjective Genetic Algorithm

In this study, the automated design optimization system is developed by using DRMOGA [2]. DRMOGA is characterized by the parallelization model where the individuals are divided into subpopulations.

DRMOGA procedure (Figure 2) can be explained as follows. First, initial individuals are produced randomly and evaluated. Second, the division of individuals is performed based on the ranking of individuals based on values of a certain objective function f_i. Assuming m subpopulations for N individuals, N/m individuals will be allocated to each subpopulation. Then in each subpopulation, the existing MOGA is performed. After MOGA is performed for k generations, all of the individuals are gathered and they are divided into subpopulations again according to the ranking based on another objective function f_j. This ranking function will be chosen in turn.

DRMOGA is known to enhance the population diversity and to produce a better Pareto front. The subdivision of the population based on alternative objective functions prevents the premature convergence to a Pareto front segment and introduces migration of individuals to neighboring Pareto front segments.

In this study, MOGA utilized real-number cording [5], the Pareto ranking method [6], BLX-0.5 [5] and Best-N selection [7] and mutation rate was set to 0.1. Function evaluations in MOGA were parallelized on SGI ORIGIN2000 supercomputer system at the Institute of Fluid Science, Tohoku University. For DRMOGA, k was set to 4 and number of subpopulation was set to 4.

2.3 Geometry definition

To generate a computational grid according to given design variables, an automated procedure to find a pipe junction from pipe centerlines was developed in the previous study [1] as shown in Figure 3. In this method, temporary background grids are first generated from the given centerlines. Then the overlap region of the pipes is calculated and removed. The advancing-front method [8] is then applied to generate the computational surface grid by specifying the junction as a front. With this method, various merging configurations can be generated only by specifying the merging points on the pipe centerline.

In this study, the initial manifold shape is taken from an existing engine with four pistons as shown in Fig. 1. Topology of the merging configuration is kept unchanged. The pipe shape traveling from the port #2 to the outlet is also fixed. Three merging points on the pipe centerlines, junctions #1-3, are considered as design variables. Pipe centerlines of #1, 3 and 4 are then deformed similarly from the initial shapes to meet the designed merging points. The pipe shapes are finally reconstructed from the given pipe radius. This method allows the automated grid generation for arbitrary merging configuration defined by the pipe centerlines.

This study considered two design cases. In the first case assumes, three merging points and the pipe radius of the entire exhaust manifold are to be designed and numbers of design variables are four. The pipe radius will vary from 83% to 122% of the original radius.

In the second case, the pipes radii are increased when pipes are merged at junctions, so pipes radii are defined at three regions as shown in Figure 4 and numbers of design variables are six; three merging points, radius r_0 defined at the region 1 and the increasing factor of radius a and b defined at the region 2 and the region 3, respectively. The pipe radius is kept constant at each region. The pipe radius r_0 will vary from 90% to 120% of the original radius, the first increasing factor a will vary from 1.06 to 1.18 and the second increasing factor b will vary from 1.35 to 1.45. These values were determined based on the actual industrial design.

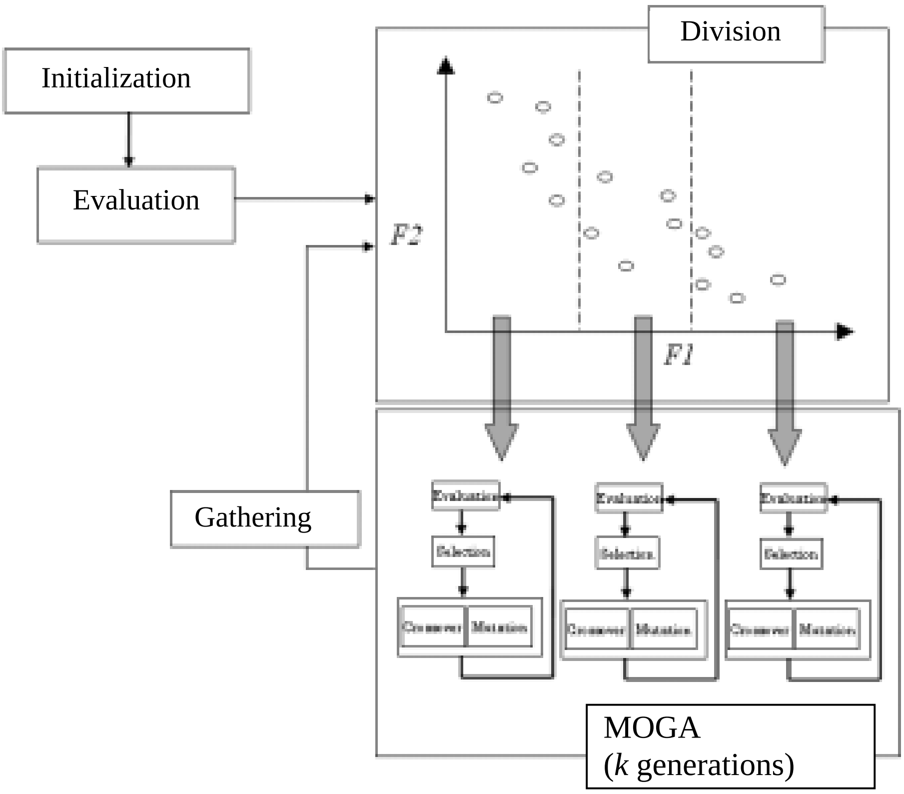

Figure 2: Procedure of DRMOGA

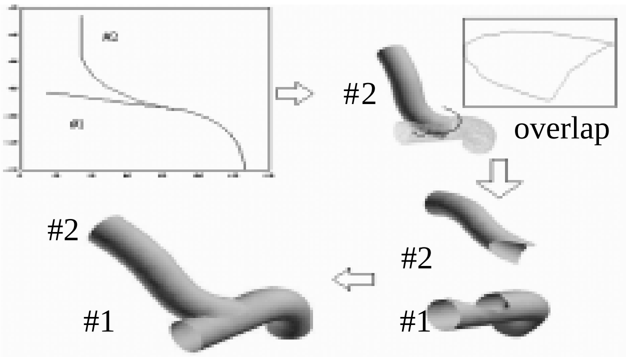

Figure 3: Surface definition with arbitrary pipe junction

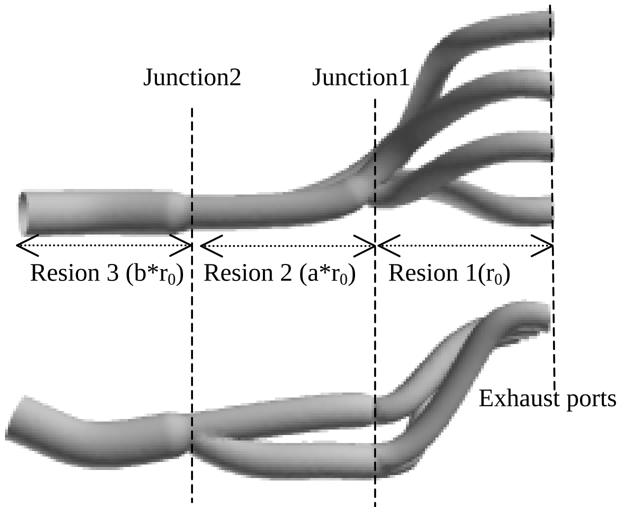

Figure 4: Geometry definition for tapered pipe

3 DESIGN OPTIMIZATION OF AN EXHAUST MANIFOLD

3.1 Design problems

In this study, two design problems were considered. First, the design optimization of merging points pipe radius were performed (Case 1). The evolution was advanced for 30 generations.

Second, the merging points and pipe radius were optimized with changing pipe radius along the exhaust manifold (Case 2). The evolution was advanced for 14 generations. In each case, the population size was set to 64.

3.2 Comparison of solution evolutions

In Case 1, Pareto solutions were found as shown in Figure 5(a). Good improvements in both objective functions were achieved. The Pareto front also confirms the tradeoff between the two objectives. This result suggests that the design of merging points and pipe radius are effective parameters to improve in both objective functions; charging efficiency that indicates the engine power and the temperature at the end of the exhaust manifold.

In Case 2, Pareto solutions were found as shown in Fig. 5(b). All solutions achieve much higher charging efficiency than the initial geometry and much better improvement in the charging efficiency than Case 1. This result shows that the tapered pipe consideration is very effective to maximize both objective functions.

3.3 Comparison of designed shapes of selected Pareto solutions

Manifold geometries taken from four Pareto solutions in Case 1 are shown in Figure 6. The initial shape is drawn with the mesh in a dark color. The solutions A and C achieved higher charging efficiency but their radii remained almost identical to the initial radius. On the other hand, the solutions B and D achieved much higher temperature and their pipe radii became larger than the initial radius. These comparisons reveal the tradeoff in maximizing the charging efficiency and the temperature of the exhaust gas.

Manifold geometries taken from three Pareto solutions in Case 2 are shown in Figure 7. The solution E achieved the highest charging efficiency in the both cases and the radius remains unchanged. While the radius of the solution F achieving highest temperature becomes large. Such tendency is similar to Case 1. The distance at region 2 of the solution E became longer than that of the initial manifold. This type of a merging configuration is expected to reduce the interaction of the exhaust gas led from chambers and thus to lead to a high charging efficiency. In contrast, the distance at region 2 of the solution F became shorter. Moreover, solution G found from Pareto center shows much better improvement in both objective functions. The radius at region 1 of the solution G was identical to the initial radius and the radius at region 3 reached to the upper limit of the factor *b*. This result suggests that an exhaust manifold which has the identical radius to the initial at region 1 and lager radius pipe at region 3 should realize less gas interaction through the complex merging pipe without reducing the temperature at the end of the manifold. The length of the region 2 was similar the length of the solution E, so the solutions located close to each other.

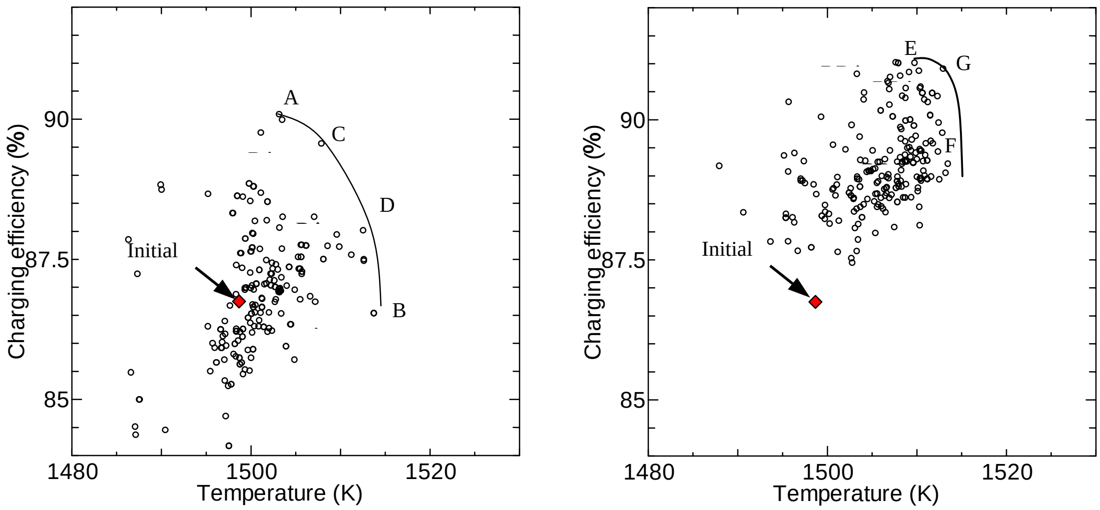

Figure5: All solutions produced by DRMOGA plotted in the objective function space; (a) Case 1, (b) Case 2

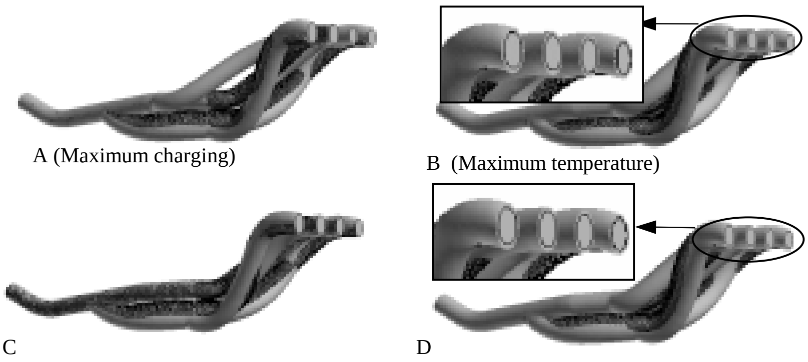

Figure6: Manifold shapes of selected from Pareto solutions in Case 1; constant radius.

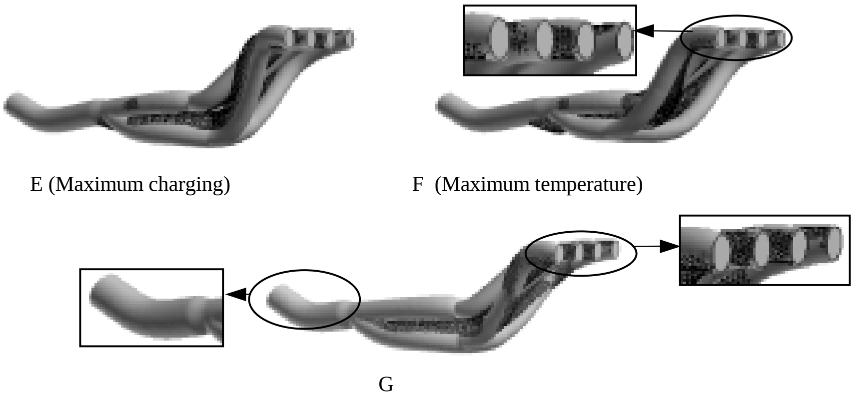

Figure7: Manifold shapes of selected from Pareto solutions in Case 2; variable radius.

4 CONCLUDING REMARKS

An improved design optimization system of an exhaust manifold of a car engine has been developed by using DRMOGA. The empirical car engine cycle simulation code was coupled with the unstructured, unsteady Euler code for evaluation of the three-dimensional manifold shapes. Computational grids were automatically generated from the designed merging points on pipe centerlines. The initial configuration of the manifold was taken from an existing high power engine with four cylinders.

At first, the manifold shape was optimized. The design variables are three merging points on the pipe centerlines and pipe radius of the entire manifold. The present system successfully found optimal solutions improved in the both objective functions considered in this study.

In the second optimization problem, the manifold is divides into three regions based on merging points and pipe radii are given separately. In this case, solutions appear better than the initial design from the beginning and most of them achieve higher charging efficiency than the solutions in Case1. This result suggests that the variable pipe radii definition is important design specification to improve both design objectives.

The present system has successfully found solutions that have less environmental impact and more engine power simultaneously than the initial design. The resulting Pareto front also reveals the tradeoff between the two objectives.

5 ACKNOWLEDGEMENTS

We would like to thank Powertrain Research Laboratory in Mazda Motor Corporation for providing the one-dimensional empirical engine cycle simulation code and the engine data. The calculations were performed by using the supercomputer, ORIGIN 2000 in the Institute of Fluid Science, Tohoku University.

REFERENCES

[1] M. Kanazaki, M. Morikawa, S. Obayashi and K. Nakahashi, "Multiobjective Design Optimization of Merging Configuration for an Exhaust Manifold of a Car Engine", *Proceedings of PPSN, the 7th international conference on parallel problem solving from nature*, in print, (2002).

[2] T. Hiroyasu, M. Miki and S. Watanabe, "The New Model of Parallel Genetic Algorithm in Multi-Objective Optimization Problems (Divided Range Multi-Objective Genetic Algorithm)," *IEEE Proceedings of the Congress on Evolutionary Computation 2000*, Vol. 1, pp.333-340, (2000).

[3] D. Sharov, and K. Nakahashi, "Reordering of 3-D Hybrid Unstructured Grids for Lower-Upper Symmetric Gauss-Seidel Computations," AIAA J., Vol. 36, No. 3, pp. 484-486, (1998).

[4] K. Ohnishi, H. Nobumoto, T. Ohsumi and M. Hitomi, "Development of Prediction Technology of Intake and Exhaust System Performance Using Computer Simulation," MAZDA Technical Paper (in Japanese), No. 6, (1988).

[5] L. J. Eshelman and J. D.Schaffer, "Real-coded genetic algorithms and interval schemata," *Foundations of Genetic Algorithms2*, Morgan Kaufmann Publishers, Inc., San Mateo, pp. 187-202, (1993).

[6] C. M. Fonseca and P. J. Fleming, "Genetic algorithms for multiobjective optimization: formulation, discussion and generalization," 5th International Conference on Genetic Algorithms, Morgan Kaufmann Publishers, San Francisco, pp. 416-423, (1993).

[7] K. A. De Jong, "An Analysis of the Behavior of a Class of Genetic Adaptive System," Doctoral Dissertation, University of Michigan, Ann Arbor, (1975).

[8] Y. Ito and K. Nakahashi, "Direct Surface Triangulation Using Stereolithography (STL) Data," AIAA Paper 2000-0924, (2000).

[9] M. Kanazaki, S. Obayashi and K. Nakahashi, "The Design Optimization of Intake/Exhaust Performance of a Car Engine Using MOGA," *Evolutionary Methods for Design, Optimization and Control, Proceedings of EUROGEN 2001*, pp. 423-428, (2001).