

Development of CFD Inverse Analysis Technology Using the Transient Adjoint Method and Its Application to Engine In-Cylinder Flow

Masato Kubota, Shigefumi Tokuda, and Yasushi Noguchi
Toyota Motor Corporation

ABSTRACT

Conventional CFD-based shape optimization technology that uses parametric shape modification and optimal solutions searching algorithms has the two problems: (1) outcome of optimized shapes depend on the selection of design parameters made by the designer, and (2) high computational costs. To resolve those problems, two innovative inverse analysis technologies based on the Adjoint Method were developed in previous study: surface geometry deformation sensitivity analysis to identify the locations to be modified, and topology optimization to generate an optimal shape for maximizing the cost function in the constrained design space. However, these technologies are only applicable to steady flows. Since most flows in a vehicle (such as engine in-cylinder flow) are transient, a practical technology for surface geometry sensitivity analysis has been developed based on the Transient Adjoint Method. This can be applied to fully transient flows like engine in-cylinder flow to calculate sensitivity distributions for arbitrary temporal performance in a targeted period utilizing transient flow results from commercially available CFD solvers. This was accomplished by introducing original discretized governing equations that are consistent with the Transient Adjoint theory and realistic flows including moving meshes and other events, as well as by developing methodologies for performing analysis stably and efficiently. This study confirmed that tumble flow rotation early in the compression stroke can be intensified taking into account pressure loss in the intake stroke of a stock engine by modifying the design shape of the intake port or piston according to the surface geometry sensitivity distribution calculated by the developed technology.

CITATION: Kubota, M., Tokuda, S., and Noguchi, Y., "Development of CFD Inverse Analysis Technology Using the Transient Adjoint Method and Its Application to Engine In-Cylinder Flow," *SAE Int. J. Engines* 9(2):2016, doi:10.4271/2016-01-0607.

INTRODUCTION

As issues related to the environment and energy continue to gain prominence, automakers are facing growing demands for high quality and safety, reduced emissions of CO₂ and the like, improved performance, and lower cost. To shorten development lead times while still achieving these goals, shape optimization technology using numerical analysis is an extremely effective means of deriving shapes in advance to satisfy the large number of target performance requirements at the initial stage of development, including those that have a trade-off relationship. This approach is also valid in the field of computational fluid dynamics (CFD).

For this reason, previous research has proposed search-based methods for shape optimization that combined CFD, parametric shape modification, and optimization algorithms such as the conjugate gradient (CG) method or genetic algorithms (GA). However, these methods had the following two major issues [1]: (1) the final shape depended on the selection of design parameters for shape modification made in advance by the designer, and (2) the lengthy time required to obtain the final shape due to the large number of calculation iterations. As an example of (2), Fig. 1 shows the results of shape optimization for an engine intake port to achieve target tumble ratio while minimizing pressure loss. Each symbol (◇) in the graph indicates an individual CFD result for a particular design.

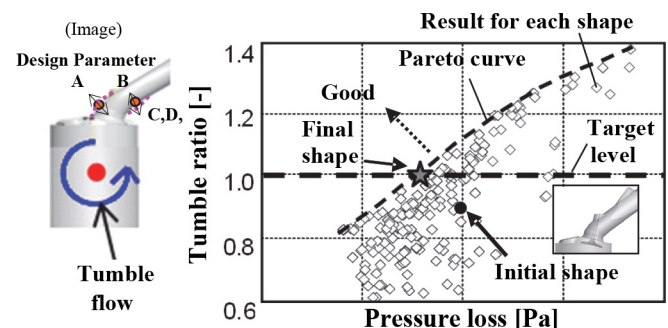


Figure 1. Results of conventional shape optimization [1].

To resolve these issues, a series of technologies based on the mathematical theory called the Adjoint Method were developed. The concept of these technologies is the inverse analysis, and directly opposite of conventional search-based optimization methods. The first was surface geometry sensitivity analysis technology using the Adjoint Method[1]. This is capable of theoretically calculating the degree of performance change for any cost function due to whole surface geometry deformations and showing where to be modified in a single calculation without making any actual deformation to the mesh model geometry to approach optimum performance from an initial shape with respect to a targeted flow. This was followed by the application of the Adjoint Method to develop topology

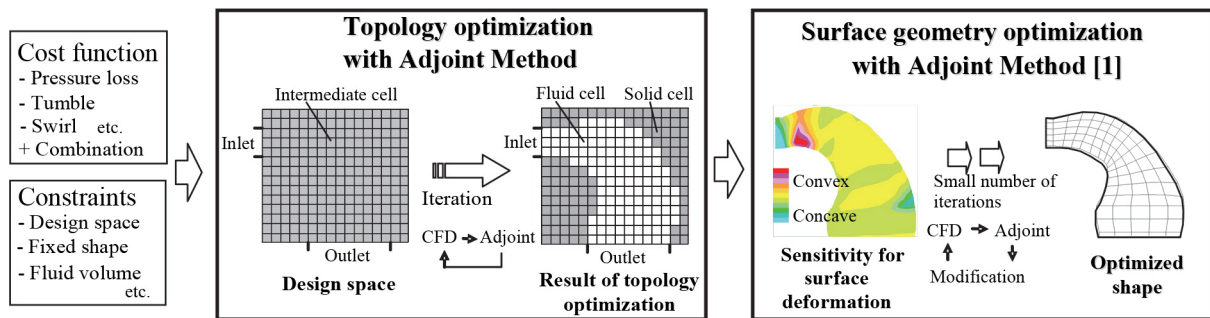


Figure 2. Process of CFD shape optimization by combining topology and surface geometry optimization with the Adjoint Method [2].

optimization technology capable of creating an ideal basic shape for optimum performance for any combination of cost functions, while considering spatial constraints [2][3]. Combining these two technologies in series resulted in an innovative shape optimization process (i.e., first using topology optimization to obtain an ideal basic flow path calculated as an iso-surface of porosity for a design space mesh, and then performing the minimum number of modifications to create the finished shape in accordance with the surface sensitivity calculated by analyzing a mesh model of the basic shape (Fig. 2)).

This process is capable of obtaining high-performance flow path shapes for parts in a much shorter period of time than conventional shape optimization calculations [1][2][3].

However, these CFD inverse analysis technologies using the Adjoint Method are only applicable to steady flows. Engine intake port optimization, which was used as a typical case in the published reports to demonstrate the effectiveness of the developed methods, can be used as an example. The left side of Fig. 3 shows the evaluation of tumble flow performance with a steady flow. This case simulates a steady flow experiment that evaluates the tumble torque in the horizontal cross-sectional plane of the cylinder extending in the downstream direction. However, it goes without saying that most of the flows in a vehicle are transient. Various transient flow phenomena have been identified, including flows within the engine, and the transient characteristics of vehicle body aerodynamic performance are also an important issue. The right of Fig. 3 shows the extent of the transient flow characteristics of tumble flow rotation in the cylinder that are required to achieve the targeted optimum engine performance. Consequently, it may be possible to propose an intake port shape with even higher performance if inverse analysis technology can be applied directly to the targeted in-cylinder phenomena, including piston shape and all transient factors such as the valve lift characteristics and piston motion. For example, it may be possible to apply inverse analysis technology to flow around the spark plug during ignition. Therefore, to resolve these issues, this research developed versatile and practical inverse analysis technology capable of being applied directly to realistic three-dimensional (3D) transient flows, such as engine in-cylinder flow.

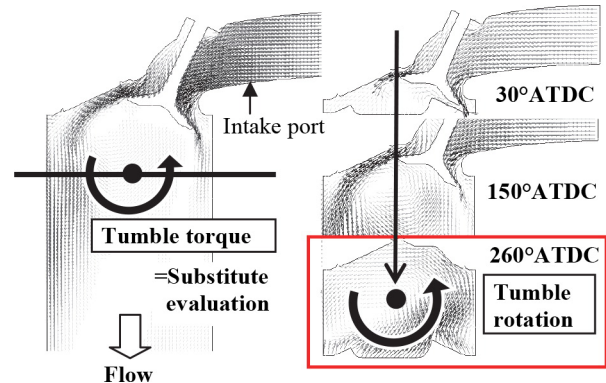


Figure 3. Steady state evaluation (left) and realistic transient evaluation (right) for engine in-cylinder tumble flow.

APPROACHES TO TRANSIENT FLOW PROBLEMS

An investigation of published research clarified that Adjoint theory could be applied mathematically to transient problems [5][6]. However, although the term “transient flow” seems like a convenient catchall phrase, it is actually divided into various different aspects. Even if a flow has clear time-based variations, these flows can still be divided into the three categories listed in Table 1 [5]. From the bottom, Flow category C involves cyclic flow variations in which time-average flows are important. In this case, it is appropriate to apply the Steady Adjoint Method after calculating the time-average of the transient flow. Flow category B includes cases in which the pulsation flow speed or part angle changes in accordance with time. These might be defined as “quasi-steady”, because they are close to steady states from individual aspects. In such cases, rather than applying extremely time consuming transient Adjoint Method, it is more appropriate to select certain time points and apply the Steady Adjoint Method, while considering the time-based effects by applying the weighting factor to sensitivities. In contrast, flow category A refers to fully transient flows with no steady factors. This category includes sudden pulsing flows and transient aerodynamics such as crosswind shocks applied to the vehicle body. Since the target of this research, i.e., engine in-cylinder flow, is a typical example of a fully transient flow, it was decided to develop transient Adjoint analysis technology.

Table 1. Approaches to transient flow using Adjoint Method.

Approach		Flow solver	Adjoint solver
A	Full unsteady	Transient	Transient
B	Weak unsteady	Transient	Steady
C	Time-average flow	Transient	Steady
		Time-average	

EXISTING RESEARCH INTO TRANSIENT ADJOINT METHOD

There are limited number of examples of research into the Transient Adjoint Method in any field. The most significant cases include research into shape optimization for 2D unsteady heat conduction problems based on surface coordinate sensitivity using thermal dissipation over time as the cost function [4], 2D wing shape optimization to minimize time-average flow resistance under cyclically varying flow [5], and sensitivity analysis of wall shapes to reduce damage to buildings caused by shock waves (time integration of window pressure) [6]. Although the targeted phenomena (i.e., the governing equations) or scale of these studies are different, they all obtained surface geometry sensitivity with respect to a cost function over the specified evaluation time period of the transient phenomenon. These studies confirmed that Transient Adjoint Method theory is applicable to realistic problems. However, the studies addressing flow fields problems were fundamentally limited to 2D wing shape optimizations, despite the existence of a report into 3D wing shapes that considered mesh deformation due to changes in the wing angle [7]. No reports were found examining realistic 3D transient flows in engines, which include the valve piston motion targeted by this research, or the like.

THEORY OF TRANSIENT ADJOINT METHOD

This section describes the theory of the Transient Adjoint Method constructed by this research based on references [5] and [6]. The basic principle uses the Lagrange multiplier method for extreme functions containing constraint conditions.

Here, when the cost function is basically expressed by state variable $\mathbf{w}$ and design variable α_k as in the steady problems, but if it is also a function of time $t(f(\mathbf{w}, \alpha_k, t))$, a new time-integrated cost function I is created for application to transient problems. That is, when t_f is defined as the terminal time for the phenomenon, as follows:

$$I = \int_0^{t_f} f(\mathbf{w}, \alpha_k, t) dt \quad (1)$$

On the other hand, the governing equation that specifies the state variable $\mathbf{w}$ was

$$\mathbf{R}(\mathbf{w}, \alpha_k) = 0 \quad (2)$$

in steady Adjoint theory where $\mathbf{R}$ is the residual, but the Transient Adjoint theory assumes that the governing equation for the transient state variable $\mathbf{w}(t)$ takes the form shown in Equation (3), with a transient term applied to the first term.

$$\frac{\partial \mathbf{w}}{\partial t} + \mathbf{R}(\mathbf{w}, \alpha_k, t) = 0 \quad (3)$$

Here, the time-integrated element on the left side of Equation (3) forms a new transient residual, as shown in Equation (4).

$$\mathbf{R}_{tran} = \int_0^{t_f} \left\{ \frac{\partial \mathbf{w}}{\partial t} + \mathbf{R}(\mathbf{w}, \alpha_k, t) \right\} dt \quad (4)$$

Here, Lagrange function L is introduced with $\lambda(t)$ as a Lagrange multiplier as shown in Equation (5).

$$L = I + \lambda^T \mathbf{R}_{tran} \quad (5)$$

By substituting I (Equation (1)) and $\mathbf{R}_{tran}$ (Equation (4)), Equations (6) and (7) are derived from the variation of L .

$$\delta L = \int_0^{t_f} \left(\frac{\partial f^T}{\partial \mathbf{w}} \delta \mathbf{w} + \frac{\partial f}{\partial \alpha_k} \delta \alpha_k \right) dt \quad (6)$$

$$+ \int_0^{t_f} \lambda^T \left(\frac{\partial}{\partial t} \delta \mathbf{w} + \frac{\partial \mathbf{R}}{\partial \mathbf{w}} \delta \mathbf{w} + \frac{\partial \mathbf{R}}{\partial \alpha_k} \delta \alpha_k \right) dt \quad (7)$$

Because the target of this research is to differentiate by the design variable α_k , (the node coordinate in the case of surface geometry sensitivity), it is meaningless to keep $\delta \mathbf{w}$ since it requires CFD to calculate $\delta \mathbf{w} / \delta \alpha_k$, thereby increasing computation costs. A way of avoiding this issue is to ensure that the coefficients applied to $\delta \mathbf{w}$ in Equations (6) and (7) always result in a total of zero. This can be expressed as the following equality relationship.

$$\frac{\partial \lambda}{\partial t} = \left(\frac{\partial \mathbf{R}}{\partial \mathbf{w}} \right)^T \lambda + \frac{\partial f}{\partial \mathbf{w}} \quad (8)$$

Since Equation (8) is the time integration equation in the time-backward direction (Fig. 4) under terminal-zero initial value conditions, the right term was considered after positive and negative inversion. This forms the transient Adjoint equation. If $\lambda(t)$ solved for the time series group (i.e., the transient Adjoint variable), the design variable sensitivity (α_k differentiation) forms the remaining terms of Equations (6) and (7) and can be calculated by the following arithmetic computation (time integration).