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Nonparametric Shape Optimization for Die Casting Using CFD Simulation

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Abstract

We propose a nonparametric curve optimization method based on a genetic algorithm. With conventional curve optimization methods, since the shape of a curve is defined by a finite number of design variables of real numbers and also has only finite flexibility, such methods may not provide the proper optimum curves. In contrast, the method we propose directly treats curves as solutions in the form of functions, without design variables, and can effectively optimize the curves by numerically synthesizing several functions. We demonstrate the effectiveness of the curve optimization method by applying it to an optimum design problem of a runner for die casting using a computational fluid dynamics (CFD) simulation.

Keywords: shape optimization, genetic algorithm, computational fluid dynamics, die casting

1. Introduction

In casting industry, computational fluid dynamics (CFD) simulations have generally been used for evaluation of the flowability of molten metal as well as the design and development of many casting products. With advances in computing power of CPUs and multiprocessing technologies, the computing time necessary for these simulations has greatly decreased, and this has made it possible to automate shape designs based on optimization theories that require multiple repeated analyses.

When the shape of a product is to be optimized, the traditionally used methods define the shape using several free curves such as spline curves and Bézier curves, and they optimize these curves by letting the coordinates of the control points of the curves be the design variables for optimization [1–3]. However, since the curves generated by these methods, which parametrically define curves using a finite number of design variables, also have finite flexibility that depends on the number of the design variables, such methods may not provide the proper optimum curves. As a way to deal with this problem, we proposed an optimization method that can nonparametrically generate curves of displacement waveform, which are single-valued functions, without any design variables [4].

In contrast, many methods of topology optimization, which can directly optimize the material layout, have been proposed for product design problems using numerical analyses, in particular structural analyses [5, 6]. These methods are nonparametric shape optimization methods and can define shapes with quite a high flexibility. However, for optimum design problems, topology optimization has the disadvantage of low compatibility with computer-aided design (CAD) software and low usefulness resulting from its discrete shape representation.

In the present study, we propose a nonparametric curve optimization method based on a genetic algorithm (GA) for shape design problems. The method we propose directly treats curves as solutions in the form of functions, without design variables, and can effectively optimize the curves by numerically synthesizing several functions. Eventually, we apply the proposed system to an optimum design problem of a runner for die casting using a CFD simulation, and demonstrate the effectiveness of the optimized shape.

2. The Curve Optimization Method

2.1 Overview

The proposed method is a curve optimization algorithm based on a GA. GAs are metaheuristic algorithms that mimic the process of the evolution of biological populations. GAs are also flexible algorithms and can be applied to quite a wide range of problems. GAs treat the solutions for a problem as individuals and search for good solutions by repeatedly breeding new individuals through genetic operations. A standard GA solves an optimization problem according to the following procedure:

1. Randomly generate the initial population of individuals.
2. Evaluate each individual in that population.
3. Stochastically select some pairs of individuals as parents according to their evaluated values.
4. Generate new individuals as children by giving genetic operations such as "crossover" and "mutation" to the parent individuals.
5. Evaluate these new individuals.
6. Go to step 3 if the termination conditions are not satisfied.

When the shapes of curves are optimized, the shapes are generally defined by several design variables of real numbers in some way—such as a B-spline curve or a Bézier curve—and then this can be boiled down to an optimization problem of a function of real numbers. When such an optimization problem is solved by using a GA, the individuals are expressed as real vectors and the genetic operations are defined as numerical processes among these vectors.

In contrast, in the proposed method, the individuals are treated directly as curves, and the crossover method, which is one of the genetic operations, is defined as a mathematical synthesis among these curves. By defining the individuals and the crossover method in these ways, the proposed method can generate curves with even more complex shapes that could not be created by the conventional methods using design variables.

2.2 Expression of curves

Let us express an open curve in an X–Y plane, which is one of the components of a shape, as the following polynomial vector function using a parameter t:

$$\mathbf{S}(t)=\sum_{i=0}^{n}\begin{bmatrix} a_i^{x} \\ a_i^{y} \end{bmatrix} t^i, \quad \text{for} \quad 0 \le t \le 1, \tag{1}$$

where n is the order of the polynomial, and a_i^x and a_i^y for $i = 1,\ldots,n$ are the coefficient of each term. Here, let us call one of the edge points $\mathbf{S}(0)$

the "start point", and also call the other edge point S(1) the "end point".

Expressing a curve using the coefficients a_i^x and a_i^y seems like a parametric description at first glance. However, that expression can in fact be said to be a nonparametric description for the two following reasons: the polynomial order n is variable due to the crossover method we propose, and the coefficients cannot be directly specified as if they were parameters but can only be changed by the crossover operation.

2.3 Initial individual

An initial individual is generated as a Bézier curve [7], which is described as the following polynomial function:

$$\mathbf{B}(t)=\sum_{i=0}^{n}\mathbf{P}_i C_i^n t^i (1-t)^{n-i}, \quad \text{for} \quad 0 \le t \le 1, \qquad (2)$$

where n is the order of the polynomial function as shown in Eq. (1), each C_i^n is a binomial coefficient and each $\mathbf{P}_i=\left[p_i^x \; p_i^y\right]^{\mathrm{T}}$ is one of the control points, which decide the shape of the Bézier curve.

When $i = 0$ or $i = n$, the control point $\mathbf{P}_i$ has the following relations: $\mathbf{P}_0$ = S(0) or $\mathbf{P}_n$ = S(1), respectively. Namely, the control points $\mathbf{P}_0$ and $\mathbf{P}_n$ correspond with the start and end points of the curve, respectively. Moreover, the straight line passing through points $\mathbf{P}_0$ and $\mathbf{P}_1$ is equal to the tangent line at the start point, and similarly, the straight line passing through points $\mathbf{P}_n$ and $\mathbf{P}_{n-1}$ is equal to the tangent line at the end point. A curve as an initial individual is generated as a Bézier curve by randomly deciding some or all of the control points of the curve.

2.4 Crossover method

As shown in Fig. 1, new child curve $\mathbf{S}_c(t)$ is generated by applying a crossover method to two parent curves $\mathbf{S}_p(t)$ and $\mathbf{S}_q(t)$. Using two parameters r_0 and r_1, the crossover method X is defined by:

$$\begin{aligned}\mathbf{S}_c(t) &= X\left(t, r_0, r_1, \mathbf{S}_p(t), \mathbf{S}_q(t)\right)\\ &= f(t,r_0,r_1)\mathbf{S}_p(t)+\left(1-f(t,r_0,r_1)\right)\mathbf{S}_q(t)\\ &\quad +(r_1-r_0)t(1-t)\\ &\quad \times\left\{\left(\mathbf{S}_p(1)-\mathbf{S}_q(1)\right)t-\left(\mathbf{S}_p(0)-\mathbf{S}_q(0)\right)(1-t)\right\},\end{aligned} \qquad (3)$$

where f is a function which decides the ratio of weight for combining the two parent curves using r_0 and r_1, that is,

$$f(t,r_0,r_1)=r_0(1-t)+r_1 t\,. \qquad (4)$$

Here, r_0 is a parameter affecting the synthesis of the curves around their start points, and the resulting start point $\mathbf{S}_c(0)$ is given by internally dividing the line segment joining $\mathbf{S}_p(0)$ and $\mathbf{S}_q(0)$ in the ratio $r_0 : (1 - r_0)$. Similarly, r_1 is a parameter affecting the synthesis of the curves around their end points, and $\mathbf{S}_c(1)$ is given by internally dividing the line segment joining $\mathbf{S}_p(1)$ and $\mathbf{S}_q(1)$ in the ratio $r_1 : (1 - r_1)$. In the case of $r_0 = r_1 = 1$, $\mathbf{S}_c(t)$ is equal to $\mathbf{S}_p(t)$, and in the case of $r_0 = r_1 = 0$, it is equal to $\mathbf{S}_q(t)$. When $r_0 = r_1 = 0.5$, the curve simply becomes the geometrically intermediate shape between $\mathbf{S}_p(t)$ and $\mathbf{S}_q(t)$.

Since the function f in Eq. (4) is a linear function of t, the generated child curve is one higher order than the parent individuals. Thus, a more complex curve can be generated by applying the crossover method repeatedly.

In optimization, by setting the values of r_0 and r_1 randomly every crossover, a random child curve is generated. As a standard, let these parameters be defined by the following equation:

$$r_i=\frac{1+R}{2}, \quad \text{for} \quad i=1,2\,, \qquad (5)$$

where R is a random number from the standard normal distribution.

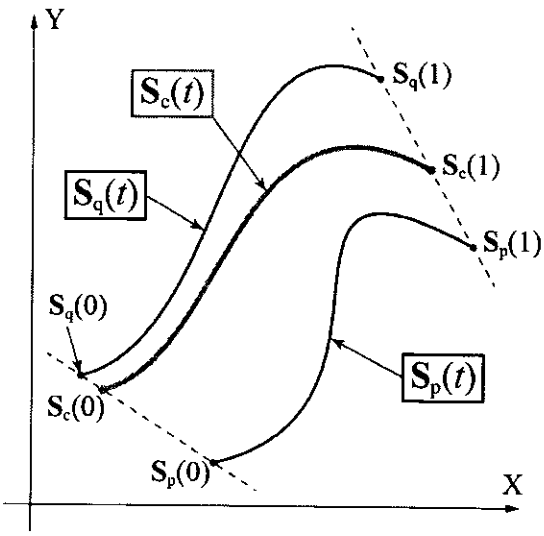

Fig. 1 Outline drawing of the proposed crossover method

$S^1(t),\ldots,S^5(t)$, and a set of the five curves becomes one individual for a GA.

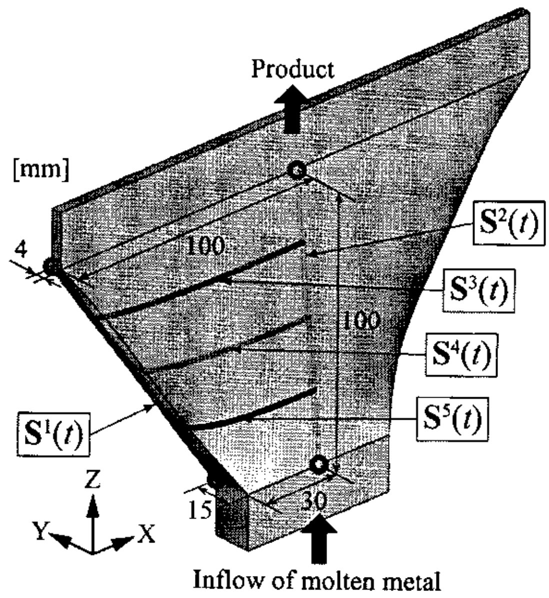

Fig. 2 Design model of the runner

3. Optimization of Runner Shape

We applied the proposed curve optimization method to an optimum design problem of a runner shape for die casting using a CFD simulation. A runner is a part of the flow path through which molten metal enters the product part. In general, it is desirable that there is no air trapping in a runner while molten metal flows through the part and that the flow reaches and passes through the tip of the runner uniformly. We derived an optimum shape of runner that can minimize air trapping in the region, to reduce air entrapment defects in products. The CFD modeling was carried out using commercial CFD software, FLOW-3D Version 10.1.

3.1 Definition of design model of runner

Fig. 2 shows the design model of the runner that was the target of optimization. The shape of this runner is defined based on the five curves $S^1(t),\ldots,S^5(t)$, and a set of the five curves becomes one individual for a GA.

Regarding the geometric constraints of the curves, both the start and end points of $S^1(t)$ and $S^2(t)$ are fixed, and those of $S^3(t)$, $S^4(t)$ and $S^5(t)$ follow $S^1(t)$ and $S^2(t)$. In addition, the tangent angles of the edge points of $S^1(t)$ and $S^2(t)$ can be freely changed, and those of the other curves are fixed. The initial individuals are generated by setting the five curves as cubic Bézier curves that meet those constraints.

3.2 Setting for CFD simulation and formulation of optimization problem

The fluid behavior and amount of air in the runner were analyzed using a CFD simulator. The parameters of the mesh block, which is an analytical region for the CFD simulation, are listed in Table 1. Since the runner is symmetrical about the Y–Z plane, the mesh block was set as only a one-sided model and this can reduce the computational time of the simulation. As for the boundary conditions of the mesh block, the bottom (–Z) boundary was set as the "specific velocity" condition, which makes fluid inflow at the constant velocity of 2.0 m/s in the Z direction. The top (+Z) boundary was set as the "specific pressure" condition at which the pressure was set to a constant value 1.013×10^5 Pa, and it allows the fluid to outflow. The other four boundary were set as the "symmetry" condition. The fluid was set as ADC12 aluminum alloy, whose properties are listed in Table 2. In addition, the fluid was incompressible and calculated as single-phase flow. For the air, the "adiabatic bubbles" model was activated, which allows each bubble pressure to be inversely proportional to its volume without applying two-phase flow. Moreover, the gravitational acceleration was –9.81 m/s^2 in the direction of the Z-axis.

The amount of air in the runner was evaluated using the following equation:

$$J = \frac{V_{\mathrm{air}}(t_{\mathrm{r}})}{F_{\mathrm{fluid}}(t_{\mathrm{f}})}, \quad (6)$$

where $V_{\mathrm{air}}(t)$ is the volume of the air or void in the analytical region at the time t, $F_{\mathrm{fluid}}(t)$ is the volume fraction of the fluid to the space in the cells on the top boundary of the mesh block also at the time t, t_{r} is the time when the fluid through the runner first reaches the top boundary, and t_{f} is the finish time of the simulation (here, t_{f} = 0.1 s).

Finally, the optimization problem is defined by the following equation:

$$\text{minimize} \quad J\left(\mathbf{S}^1(t),\ldots,\mathbf{S}^5(t)\right). \quad (7)$$

This optimization problem is solved by a combination of the proposed method and a standard GA, whose parameters are listed in Table 3.

Table 1 Setting parameters for the mesh block

Direction	Cell size [m]	Number of cells
X	0.00125	82
Y	0.00125	16
Z	0.00125	96
Total	–	125,952

Table 2 Properties of the fluid (ADC12).

Density	2471 kg/m^3
Viscosity	0.00125 Pa·s
Surface tension properties	N/A

Table 3 Parameters for the optimization algorithm.

Maximum number of generations	20
Number of individuals per generations	100
Number of elite individuals	10
Selection method	Tournament Selection

3.3 Optimization result

The shape and simulation results of the optimized runner are shown in Fig. 3. The figure also shows those of a standard runner for comparison. The evaluation values of the optimized and standard runners were 7.318 and 18.602, which indicate the optimized runner is superior to the other in terms of decreasing air trapping. In fact, as shown in Fig. 3, the standard runner had relatively large amount of trapped air bubbles inside at the finish time, whereas the optimized runner almost filled with the fluid without air. We thus expect that the actual amount of entrapped air would be reduced by using this optimized runner.

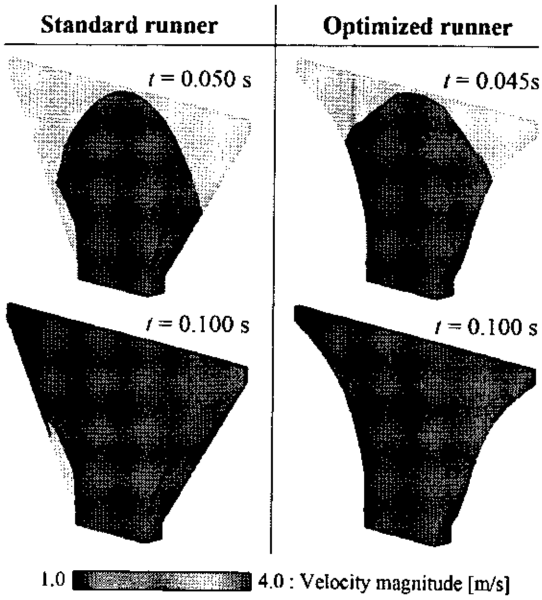

Fig. 3 Simulation results with the standard and optimized runner

4. Conclusions

We constructed a nonparametric shape optimization method for curves based on a genetic algorithm. This method can generate optimum curves with a lot of flexibility by defining a curve as a set of two parametric functions and by repeatedly applying the proposed crossover method to these curves. We applied the proposed method to an optimum design problem of the shape of a runner for die casting, and we obtained an optimized shape of the runner that effectively reduced air entrapment.

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