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Inverse prediction and optimization of flow control conditions for confined spaces using a CFD-based genetic algorithm

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ABSTRACT

Optimizing an indoor flow pattern according to specific design goals requires systematic evaluation and prediction of the influences of critical flow control conditions such as flow inlet temperature and velocity. In order to identify the best flow control conditions, conventional approach simulates a large number of flow scenarios with different boundary conditions. This paper proposes a method that combines the genetic algorithm (GA) with computational fluid dynamics (CFD) technique, which can efficiently predict and optimize the flow inlet conditions with various objective functions. A coupled simulation platform based on GenOpt (GA program) and Fluent (CFD program) was developed, in which the GA was improved to reduce the required CFD simulations. A mixing convection case in a confined space was used to evaluate the performance of the developed program. The study shows that the method can predict accurately the inlet boundary conditions, with given controlling variable values in the space, with fewer CFD cases. The results reveal that the accuracy of inverse prediction is influenced by the error of CFD simulation that need be controlled within 15%. The study further used the Predicted Mean Vote (PMV) as the cost function to optimize the inlet boundary conditions (e.g., supply velocity, temperature, and angle) of the mixing convection case as well as two more realistic aircraft cabin cases. It presents interesting optimal correlations among those controlling parameters.

1. Introduction

With rapid developments in fluid dynamics, numerical science and computer technologies, computational fluid dynamics (CFD) has become an efficient tool for indoor environment study and system design. Optimizing an indoor flow pattern according to specific design goals requires systematic evaluation and prediction of the influences of critical flow control conditions such as flow inlet temperature, velocity and angle. In order to identify the best flow control conditions, conventional approach simulates a large number of flow scenarios with different boundary conditions. Previous studies reveal advanced search and optimization algorithms such as genetic algorithm (GA) can effectively reduce the total number of iterations to reach an (or a group of) optimal solution(s) [1]. GA is an optimization algorithm that simulates natural evolution in the search of optimal solutions [2]. It has been applied to a variety of engineering design, parameter identification and system optimization. Efforts of coupling GA with CFD, however, were mostly on the optimization of exterior geometries of various objects. For instance, Obayashi and Takanashi [3] combined GA with CFD to optimize the target pressure distributions of an airfoil. Other examples include the shape design of cars [4], melt blowing slot die [5], and transition piece [6].

Malkawi et al. [7] used the CFD-based GA method to search the optimal room size and ventilation system which can satisfy both thermal and ventilation requirements. The study was for a relatively simple case and did not evaluate the influence of CFD prediction error on optimal design. Kato and Lee [8] applied a similar approach to optimizing a hybrid air-conditioning system with natural ventilation. The study aimed at minimizing the energy consumption of the mechanical systems. The study developed a two-step method to reduce the computing effort. Optimal results were acquired first with a coarse CFD mesh, which were then refined with a fine mesh for detailed analyses. It should be noted that CFD results with coarse meshes may produce incorrect flow field which can lead to wrong optimal results. Zhou and Haghighat [9,10] employed the artificial neural network (ANN) to reduce the

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modeling time; however, training the ANN still requires a great number of CFD cases for individual projects.

This study develops a general simulation tool by integrating GA and CFD programs. The tool can inversely predict control conditions based on limited experiment data of indoor flow field. It can also be used to optimize various control conditions of indoor flows under different objective functions (PMV in this paper). The tested control conditions include supply velocity (vector) and temperature of flow inlet, etc. Locally optimal solutions and multiple solutions may exist for multi-variable optimization problems, where the GA presents the special strength in capturing the global optimal results and multiple solutions.

2. Methodologies

2.1. Modified genetic algorithm

There are generally two categories of optimization algorithms: gradient-based method and gradient-free method. Gradient-based methods cannot deal with nonlinear problems well [11] and can be easily trapped in local optimal values [12]. Airflow and heat transfer problems in confined spaces are highly nonlinear and thus require the utilization of gradient-free methods. As one of the gradient-free methods, genetic algorithm is capable of resolving nonlinear and multi-solution problems, requiring less computing time to find global optimum than other methods [13]. Genetic algorithm uses evolution operations to generate new populations with higher average fitness values [14]. The higher fitness value an individual possesses, the closer it is to the optimal result. A typical GA procedure breaks down as follows:

(1) Generate a random initial population of potential solutions, which contains several individuals;
(2) Evaluate the fitness value of each individual with specified cost function;
(3) Check whether the population meets the prescribed optimization criterion; if not, apply genetic operations such as selection, crossover, and mutation to the population to create a new generation of potential solutions;
(4) Repeat step (2) and (3) until the optimization criterion is met.

The standard GA encounters several challenges when used for indoor environments. In the procedure of coding, a basic genetic algorithm usually encodes multi-variables into one long binary code. This requires large computing memory and resource for a multi-variable case. With all of variables coded in one long code, a standard GA crossovers code of each individual at one or several points randomly. This is a totally random procedure that is good for variation but discourages the convergence approaching optimum(s). The standard GA often use the roulette wheel selection method to choose suitable parents for creating next population, implying that the higher fitness value an individual has, the higher probability it will be chosen as a parent to create the new generation of individuals. This may be suitable for individuals with a large fitness value difference, but may illustrate the character of random selection and lose the benefits of evolution when the differences are marginal. Airflow and heat transfer in confined spaces involve multi-variables. These variables can have continuous changes, and may lead to small differences in fitness values among individuals. Indeed, most inverse prediction and optimization problems for indoor environment may involve subtle fine-tuning of critical flow control conditions. Hence, the standard GA need be improved to ensure a better convergence.

The study improves the coding, selection and crossover procedure to accelerate the optimization convergence speed and reduce the computing effort (Fig. 1). For the coding, various variables were encoded and managed independently. This made it easy to conduct GA operations on each of them. For the selection, the roulette wheel selection method was replaced by the tournament-selection-method, which works as follows:

(1) Pick out m individuals randomly from the current population (containing n individuals) to form a subset, where $2 \leqq m < n$;
(2) Identify the individual with the highest fitness value from the subset as one of the parents;
(3) Repeat the step (1) and (2) until n individuals are obtained (allow repeated individuals in the selected n individuals).

The obtained n individuals form the parent population that will be used to generate a new population with crossover and mutation. In this way, individuals with a higher fitness value will be chosen even if there are little differences between any two individuals. In addition, at least $m-1$ individuals with the lowest fitness values will be rejected, which makes it possible to balance the optimization convergence speed and the global search capability of the algorithm.

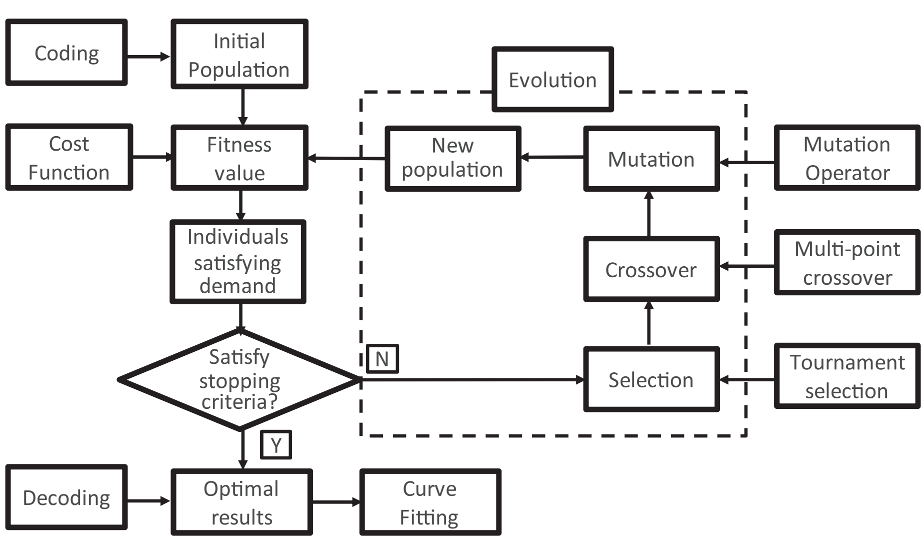

Fig. 1. Flowchart of the modified GA.