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Original Article

Application of Multivariate Adaptive Regression Spline-Assisted Objective Function on Optimization of Heat Transfer Rate Around a Cylinder

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A B S T R A C T

The present study aims to predict the heat transfer characteristics around a square cylinder with different corner radii using multivariate adaptive regression splines (MARS). Further, the MARS-generated objective function is optimized by particle swarm optimization. The data for the prediction are taken from the recently published article by the present authors [P. Dey, A. Sarkar, A.K. Das, Development of GEP and ANN model to predict the unsteady forced convection over a cylinder, Neural Comput. Appl. (2015) 1–13]. Further, the MARS model is compared with artificial neural network and gene expression programming. It has been found that the MARS model is very efficient in predicting the heat transfer characteristics. It has also been found that MARS is more efficient than artificial neural network and gene expression programming in predicting the forced convection data, and also particle swarm optimization can efficiently optimize the heat transfer rate.

1. Introduction

Nowadays, research on fluid flow and heat transfer characteristics over a cylindrical bluff body attracts tremendous attention of researchers, as it has overwhelming engineering significance for nuclear reactors, heat exchangers, natural circulation boilers, solar heating systems, electronic cooling, dry cooling towers, flow dividers, probes, vortex flow meters, sensors, etc. The common geometrical shape of a cylindrical bluff body may be circular, sharp and rounded cornered square cylindrical, triangular, etc. A square cylinder is the most common sharp-edge body and has widely been investigated in the study of fluid flow and heat transfer. Preceding studies were carried out by numerical, theoretical, and experimental methods. Based on the Reynolds and Prandtl numbers, various flow regimes were recognized in the available studies [1–10]. Also, there are various available studies associated with the circular cylinder that accomplished by the both numerically and experimentally [11–16]. Currently, fluid flow studies have found that the fluid forces

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acting on a square cylinder can be reduced by rounding the corners [17,18].

Soft computing methods have extensively been used in many areas of mechanical engineering due to their capacity of calculation and data handling. Different strategies are utilized as a part of the forecast, among them artificial neural network (ANN) and gene expression programming (GEP) being the foremost strategies in use. In order to avoid solution methods that are time consuming and need high numbers of iterations, ANN and GEP have increasingly been preferred by researchers. GEP is another framework having the upsides of both genetic programming and genetic algorithm (GA) to assess more mind boggling capacities to display a declaration of the connection between the input and output data [19]. GEP is more useful in predicting the output than ANN, as was recently discovered [20,21]. The GEP model has also been successfully employed to predict various engineering parameters [22–24]. Both models have been effectually applied, even though they have some disadvantages. One of the main disadvantages of ANN is it does not disclose any mathematical relation between the input and output variables of the system. The disadvantage of GEP is that it can generate a highly nonlinear mathematical relation between the input and output data. The multivariate adaptive regression splines (MARS) model has some advantages over ANN and GEP [25,26].

Recently, different optimization techniques, such as GA, particle swarm optimization (PSO), etc., have been applied successfully for optimizing heat transfer [27,28]. GA has been used by different researchers to optimize the convective thermal performance of fin and plate fin heat exchangers. To date, PSO has been applied to thermodynamic optimization of a cross-flow plate fin heat exchanger [29]. A comparison study of GA and PSO has been performed recently [30], and it was found that PSO is more efficient than GA for optimizing the geometry of a longitudinal fin.

Numerical, analytical, and experimental studies require much accomplishment time, and ANN and GEP have some disadvantages, therefore, the MARS model has been used in the present study to predict the heat transfer characteristics around a rounded cornered square cylinder including a square and a circular cylinder. To the best of the authors' knowledge, this is the first study on the application of MARS for the prediction of heat transfer characteristics. A total of 36 data records are collected from the recent paper published by the present authors. Further, the present prediction models are compared with the published ANN and GEP models. The relation between the input and output generated by the MARS model is then used in the PSO tool for optimizing the heat transfer rate.

2. Multivariate adaptive regression splines

MARS, a nonlinear and nonparametric regression organization, was first presented by Fridedman [31] as a supple process that replicates interactions between inputs and outputs with fewer variables. This technique creates no ambiguity about the functional connection between the dependent and independent variables; MARS develop this relationship from a group of coefficients and basis functions that are engaged from the regression data. MARS produce basis functions by examining them in a stepwise method. Each spline function is defined on a given interval and the end points of the interval are called "knots." A MARS model is completed in two steps. In the first step, the model is built and basis functions are added to grow the complexity until extreme complexity is attained. In the next step, a backward calculation is done to remove the minimum substantial basis function from the model.

The principle of the MARS system is built on piecewise linear basis functions of the following forms:

$$|x-t|_+ = \max(0, x-t) = \begin{cases} x-t & x>t \\ 0 & x \le t \end{cases} \tag{1}$$

$$|t-x|_+ = \max(0, t-x) = \begin{cases} t-x & x<t \\ 0 & x \ge t \end{cases} \tag{2}$$

where t represents the "knots." The above formulations serve as the basis functions for linear or nonlinear development that estimates the function $f(x)$.

If a dependent variable (i.e., the outcome) "y" is dependent on "M" terms, then the MARS model can be summarized in the following equation:

$$y = f(x) = \beta_0 + \sum_{i=1}^{M} \beta_i H_{ki}\left(x_{\upsilon(k,i)}\right) \tag{3}$$

where β_0 and β_i are the basis function parameters of the model, and the function H can be defined as follows:

$$H_{ki}\left(x_{\upsilon(k,i)}\right) = \prod_k -i^k h_{ki} \tag{4}$$

where $x_{\upsilon(k,i)}$ is the predictor in the k^{th} of the i^{th} product. For order of interactions $K = 1$ the model is additive, and for $K = 2$ the model is pairwise interactive [31].

2.1. *Input and output parameters*

It is necessary to have a set of data to train the predictive models, and some portion of that set is further used to test the trained models to verify their accuracy. In the present study, the input parameters are the nondimensional corner radius (r) of the square cylinder and Prandtl number (Pr). Six values of "r" were selected: $r = 0.5$ (circular cylinder), $r = 0.51$, $r = 0.54$, $r = 0.59$, $r = 0.64$, and $r = 0.71$ (square cylinder); the values of Pr varied as 0.01, 0.1, 1, 10, 100, and 1,000 at Reynolds number (Re) = 100. By combining all the inputs, a total of 36 data (6 values of "r" × 6 values of "Pr") were found. All the 36 data sets were collected from the authors' published article [32], where the data sets were established by solving the heat transfer problem numerically using the finite volume method (FVM) code. The governing equations associated with the heat transfer problem were the Navier–Stokes equations and the energy equation. The problem was solved in a two-dimensional unsteady laminar flow regime. A number of trials were performed to find a quite accurate data set to train the model. After achieving quite satisfactory accuracy, 70% of the total data were selected for training and the remaining 30% for testing the model. The single output of the present study, the heat transfer characteristics around the

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