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A surrogate model for thermal characteristics of stratospheric airship

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Abstract

A simple and accurate surrogate model is extremely needed to reduce the analysis complexity of thermal characteristics for a stratospheric airship. In this paper, a surrogate model based on the Least Squares Support Vector Regression (LSSVR) is proposed. The Gravitational Search Algorithm (GSA) is used to optimize hyper parameters. A novel framework consisting of a preprocessing classifier and two regression models is designed to train the surrogate model. Various temperature datasets of the airship envelope and the internal gas are obtained by a three-dimensional transient model for thermal characteristics. Using these thermal datasets, two-factor and multi-factor surrogate models are trained and several comparison simulations are conducted. Results illustrate that the surrogate models based on LSSVR-GSA have good fitting and generalization abilities. The pre-treated classification strategy proposed in this paper plays a significant role in improving the accuracy of the surrogate model.

Keywords: Stratospheric airship; Surrogate model; Thermal characteristics; Least squares support vector regression; Gravitational search algorithm; Learning algorithm

1. Introduction

Stratospheric airship has a broad application prospect in various fields, such as ground observation, airborne surveillance, early warning and communication relay (Li et al., 2016). At the altitude of around 20 km, the wind field is stable and suitable for the station keeping of stratospheric airships (Smith et al., 2011; Androulakakis and Judy, 2013) and high-altitude balloons (Cathey, 2009; Weiss and Todd, 2014) for a long time. However, diurnal temperature variation causes the thermal characteristics of stratospheric airships to be sensitive to the environment (Dai et al., 2016). The temperature of internal gas is much higher than the environment's, especially in the daytime due to solar radiation. This phenomenon is called superheat (Wu et al., 2015a,b). Over pressure developed by the superheat due to diurnal temperature variations significantly affects the mechanical strength of the airship envelope. Therefore, the study on thermal characteristics is of significance for the design and flight of stratospheric airships.

Due to the high cost and complexity of flight tests, only few scholars and organizations (e.g., Harada et al., 2003) around the world could obtain the real thermal data. Therefore, studies of thermal characteristics and superheat of airships are mostly based on simulation. Many thermal models have been established, such as zero-dimensional (Kreider and Box, 1975), one-dimensional (Rapert, 1987), two-dimensional (Harada et al., 2003), three-dimensional (Lee et al., 2006), transient and steady state models (Franco and Cathey, 2004; Alam and Pant, 2017). Yao et al. (2014) proposed a multi-node heat transient model and predicted the thermal behaviors of ascent and descent

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processes. They assumed the airship as two nodes, namely the air and the helium. However, they did not consider the temperature distribution of the airship envelope. Yang et al. (2015) and Yang (2016) studied the supercool and superheat behaviors of stratospheric airships during the ascent. They took solar radiation, infrared radiation and heat convection into consideration. However, their models were based on multi-node, hence obtaining 3-D temperature distribution could not be possible. Xing et al. (2017) and Liu et al. (2017) proposed a photovoltaic array model and simulated the thermal distribution of the stratospheric airship. They also took the flight speed into account. In these simulations, it can be seen that several factors, such as flight states (real-time velocity or flight attitude) and environment conditions (solar radiation or atmospheric temperature), play important roles in the thermal characteristics and performance of airships. In order to reduce the superheat effect, which is a thermal optimization problem, it is necessary to change each factor for obtaining the best parameter combination. It may take a long time to directly apply these complex models to an optimization problem which needs to conduct simulation processes thousands of times. The time cost and accuracy of calculation must be considered together, especially for a large-scale optimization. However, there is no paper introducing method based on surrogate modeling for thermal analysis to simplify calculations, and little work has been done to use them to study stratospheric airships, either. In this paper, a feasible approach based on surrogate modeling is developed to substitute simulation models and to acquire accurate thermal characteristics of stratospheric airships quickly.

Since the thermal simulation model can easily provide large series of temperature data for a limited time, it is suitable to investigate the surrogate model based on these datasets. The surrogate model introduced in this work integrates the Least Squares Support Vector Regression (LSSVR) and the Gravitational Search Algorithm (GSA). The support vectors method, which transforms low dimensional nonlinear projection into high dimensional space through a kernel function and treats the highly nonlinear problem by simple linear methods in high dimensional space, has rigorous theoretical basis and good generalization performance (Guo and Bai, 2009). The GSA is developed recently for heuristic search and optimization problem, whose mechanism is based on the interaction of two objects according to the law of gravitation (Esmat and Saryazdi, 2012). In this paper, the support vector is utilized to establish the surrogate model, the gravitational search algorithm is applied to optimize hyper parameters, and varieties of datasets provided by the thermal simulation model are used to train the surrogate model. Despite the fact that using large amounts of data as well as the search algorithm is beneficial to train the surrogate model, it is also difficult to improve the generalization ability by directly applying a support vector machine or regression model alone. Especially for a stratospheric airship, whose thermal characteristics data are of high nonlinearity, under-fitting phenomenon arises easily then the surrogate model is invalid. Therefore, a framework with pre-treated classification strategy, consisting of a preprocessing classifier and two following regression models, is designed to reduce the influences of irrelevant data and to improve the accuracy of the surrogate model.

This paper is organized as follow. A three-dimensional transient model for thermal characteristics of a stratospheric airship, considering some factors such as direct radiation, diffuse radiation, reflected radiation, infrared radiation and heat convection, is established in Section 2. The principles of LSSVR and GSA are introduced in Section 3. A training framework which contains a preprocessing classifier and two regression models is also designed in Section 3. Section 4 is devoted to presenting the simulation results of thermal models, training two-factor and multifactor surrogate models, and verifying the accuracy and effectiveness of the surrogate models above. In addition, some discussion and analysis about factors, namely the pre-treated classification strategy, the size of training data and the learning rate, are also given in this section. In the last section, a brief summary is provided.

2. Thermal characteristics modeling

A typical stratospheric airship contains envelope, ballonets, solar array, propulsion, avionics and some other subsystems (Zhao et al., 2016). There are complex heat and energy exchanges between the external atmosphere and these subsystems (Wu et al., 2015a,b). In order to simplify the simulation model for thermal characteristics and reduce the complexity of superheat effects, some assumptions on the stratospheric airship are proposed as follow:

(1) Rigid envelope assumption: the elastic deformation of the envelope surface is ignored.
(2) Ideal gas assumption: the internal gas follows the ideal gas law, and the temperature and pressure distributions of ballonets are uniform respectively.
(3) Heat transfer assumption: the heat from solar power, propulsion, avionics and other subsystems has been fully suppressed and isolated, and their influences on the thermal characteristics of the envelope are ignored. This paper only considers the heat and energy transfer between the envelope material, ballonets and the internal gas.
(4) Transient equilibrium assumption: the gas pressure balance and heat transmission processes are instantaneously completed in the air ballonet and the helium ballonet.

Based on the assumptions above, thermal characteristics of stratospheric airships are comprehensively influenced by the following factors (Hong et al., 2015): direct solar radiation, atmospheric diffuse radiation, clouds and ground reflected radiation, infrared radiation of atmosphere and ground, infrared radiation of the envelope surface, external

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