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Research Paper

Dynamic heat load calculation of a bridge anti-icing system

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HIGHLIGHTS

- An inverse heat conduction method was developed to identify the heating load.
- Heat transfer in a bridge was studied using forward and inverse methods.
- Heating load calculated was validated by two traditional control strategies.

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ABSTRACT

Road icing poses a serious threat to traffic safety in winter. Active anti-icing is one of effective methods to solve this problem. An inverse heat conduction method was developed to identify the dynamic heat load of the bridge cable heating system. One regularized functional was established based on Tikhonov regularization theory and solved by an iterative method. The results showed that the heat load calculated was not just the sum of heat loss at the top surface and bottom surface of a bridge. There are time lag and amplitude attenuation between the heat load and heat loss of the bridge. The inverse heat conduction method was validated by the direct heat transfer numerical simulation. Based on the maximum heat load results, ON-OFF algorithm and proportional-integral-derivative (PID) control algorithm were implemented. The simulation results showed that the temperature of bridge surface was greater than 0 °C and indicated that the theoretical derivation of heating load and control logic is suitable for bridge anti-icing system.

1. Introduction

In winter the road is prone to freeze due to the low temperature, high precipitation and high air humidity in some provinces in the south of the Yangtze River such as Hunan, Chongqing and Sichuan [1]. Icing would reduce the friction coefficient between the road and the tyre and bring a great threat to traffic safety [2].

Snow melt agent and snowplows are the traditional ways to make driving safer and road cleaner. These two means are simple but would have damage to the road and could not clear the snow and ice timely. Thermal anti-icing technology is an initiative method by using external thermal energy to heat the road and keep the pavement temperature always higher than 0 °C, that is, before the storm begin or during the storm thermal anti-icing technology can prevent or delay the pavement freezing [3].

Theoretical analysis method to compute the heat load is the general approaches to thermal anti-icing system which is based on the climate data, the temperature field of the pavement and the heat load. The method was introduced by American engineer F.S. Barber [4]. He considered the pavement as a semi-infinite and derived the pavement temperature field calculation formulate based on atmospheric temperature and solar radiation. But the calculation results are not applicable to low-temperature processes. Many other researchers made achievements in this area. For example, Pretorius analyzed the temperature field by the finite element method [5], Yan studied the one-dimensional temperature field of concrete pavement [6], Qin and Sun applied a prediction model to asphalt pavement in China based on statistical analysis [7], Jia et al. achieved the numerical prediction of the two-dimension unsteady state temperature of asphalt pavement affected by the natural environment [8].

The heat load is the basic knowledge of a road anti-icing system design. It would be influenced by the external climatic conditions and the structure of the pavement. Chapman model, Kilkis model and Romsey model are classic models used to calculate the snow melting and anti-icing heating load. Chapman model is widely used in engineering practice, but does not reflect the dynamic characteristics of snow and ice melting process [9]. Kilkis model is an improvement on Chapman model and reduces the

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requirement of the calculation parameters [10]. Romsey model is put forward under the ASHRAE snow melting project and focuses on theoretical study [11]. Those three models have a common characteristic that is the steady state equation is established based on energy balance principle. Recently, many researchers have simulated the dynamic temperature field and try to obtain the heat load. Nevertheless, the thermal inertia of the pavement structure was not considered adequately and the difference between the heat load and the heat loss of the pavement is ignored.

In this paper, the time lag of heat transfer and the heat capacity of the bridge would be considered fully during the pavement temperature field and heat load calculation processes. The Direct Heat Conduction Problem (DHCP) was used to solve the temperature field of a bridge deck. The heating load of anti-icing system was derived by the inverse heat conduction theory. The inverse heat conduction problem (IHCD) is the frontier and hot spot of inverse problem research [12]. The first literature on IHCDs published in 1960 by Stolz. Ill posedness is the greatest difficulty in solving the IHCD. In this paper, Tikhonov regularization function was introduced to calculate the heating load. Tikhonov regularization can effectively solve the stable solution and reduce the computation time [13].

To ensure the efficient of the road anti-icing system, choosing an appropriate control method is also very important. The control design of the road anti-icing system need to know the main input interference, the conditions of the heating system to start, input power, etc. [14]. Generally, consider the design of highway bridge automatic control can be carried out through the lanes of the bridge surface temperature changes in real time. But it is difficult to realize the effective anti-icing based on bridge surface temperature, which has a lot of defects and cause a waste of energy. In this paper, we designed two kinds of control algorithms for the bridge anti-icing system.

2. The solution of transient temperature field

2.1. Mathematical model of the DHCP

The Direct Heat Conduction Problem (DHCP) is used to solve the temperature field when the material physical properties, initial condition, and boundary conditions are completely given [15]. The transient temperature field of bridge surface can be calculated by Fourier heat conduction equation.

The thickness of the bridge is very small compared to the width and length of the bridge, therefore, the heat conduction of the bridge can be considered as one dimensional transient heat conduction process along the thickness direction. The governing differential equation is as defined by Eq. (1):

$$\frac{\partial t}{\partial \tau} = a\frac{\partial^2 t}{\partial x^2} + \frac{\dot{\Phi}}{\rho c} \tag{1}$$

where t is temperature (°C); τ is time (s); x is the coordinates (m); ρ is density (kg/m^3); c is specific heat capacity at constant pressure (J/kg·K); a is thermal diffusivity (m^2/s), $a = \lambda/(\rho c)$; λ is conductivity of materials W/(m·K); $\dot{\Phi}$ is the heat-intensity of electric heater (W/m^3).

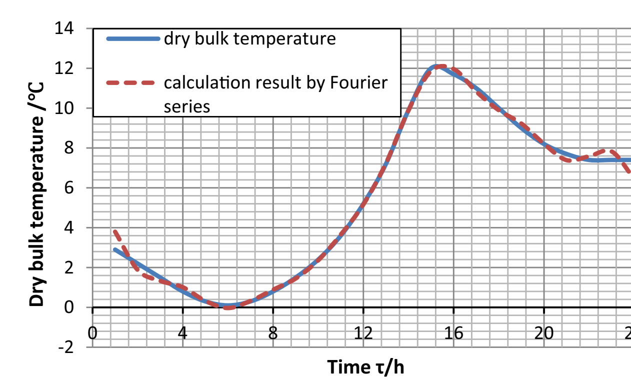
2.2. Boundary condition treatment

From the theory of transient heat conduction, the initial temperature distribution would have a great influence on the non-regular regime of heat transfer. When the heat transfer progress into the regular regime, the temperature distribution in the object would be mainly affected by the boundary conditions; and would have little relationship with initial conditions [16]. Generally, the whole process of heat conduction in bridge can be considered as a regular regime. So this paper mainly analyzes the influence of the boundary condition on the temperature distribution of the bridge.

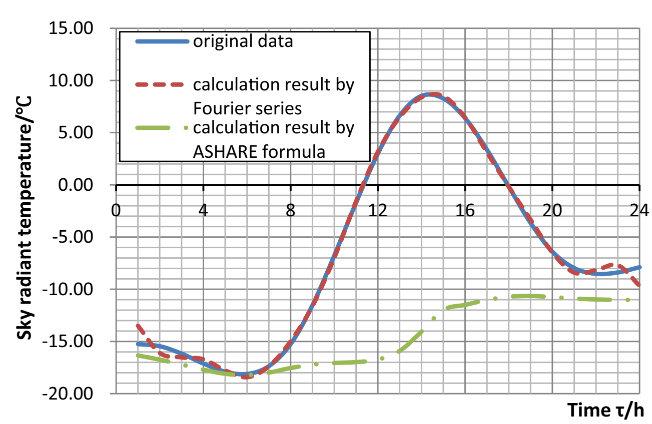
The temperature distribution of the bridge is mainly determined by the dry bulb temperature of the surrounding atmosphere, the sky radiation temperature, atmospheric humidity and moisture content of bridge body. The dry bulb temperature and sky radiation temperature are the main influence factors, such as atmospheric humidity and cloud cover are the indirect manifestation of sky radiation temperature. The meteorological data of typical coldest month was used as the basis of our simulation boundary condition, as shown in Fig. 1. The minimum value of dry bulb temperature in this region is 0.1 °C, the sky radiation temperature is −18.12 °C, which occurred at 06:00. From the original meteorological data, the weather dry bulb temperature and the sky radiation temperature are time-vary random distribution. In order to figure out the influence of initial condition on the temperature distribution of the bridge, periodic boundary condition was adopted. Therefore in our study, the meteorological parameters were expanded into periodic functions in the form of discrete Fourier series (6 orders), involving a 24 h cycle, as shown in Eqs. (2) and (3). The comparison of simulation results and measured values are presented in Fig. 1. The difference between them is very small, meeting the requirements for the calculation.

6 order Fourier series of dry bulb temperature:

$$\begin{aligned} t_{air} = {} & 5.4375 + 5.4178\cos(\omega\tau - 4.6211) + 0.8632\cos(2\omega\tau - 1.2635) \\ & + 0.9855\cos(3\omega\tau + 0.5939) + 0.3043\cos(4\omega\tau - 4.4774) \\ & + 0.3361\cos(5\omega\tau + 0.3647) + 0.3190\cos(6\omega\tau + 0.9901) \end{aligned} \tag{2}$$



(a) Dry bulk temperature



(b) Sky radiant temperature

Fig. 1. Meteorological parameters.