Optics and Laser Technology 103 (2018) 251–259

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Multispectral radiation envelope characteristics of aerial infrared targets

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ARTICLE INFO

Article history:
Received 27 October 2017
Received in revised form 31 December 2017
Accepted 4 January 2018

Keywords:
Multispectral radiation
Temperature distribution
Detection angle
Envelope characteristic

ABSTRACT

Multispectral detection signals are relatively stable and complementary to single spectral detection signals with deficiencies of severe scintillation and poor anti-interference. To take advantage of multispectral radiation characteristics in the application of infrared target detection, the concept of a multispectral radiation envelope is proposed. To build the multispectral radiation envelope model, the temperature distribution of an aerial infrared target is calculated first. By considering the coupling heat transfer process, the heat balance equation is built by using the node network, and the convective heat transfer laws as a function of target speed are uncovered. Then, the tail flame temperature distribution model is built and the temperature distributions at different horizontal distances are calculated. Second, to obtain the optimal detection angles, envelope models of reflected background multispectral radiation and target multispectral radiation are built. Finally, the envelope characteristics of the aerial target multispectral radiation are analyzed in different wavebands in detail. The results we obtained reflect Wien's displacement law and prove the effectiveness and reasonableness of the envelope model, and also indicate that the major difference between multispectral wavebands is greatly influenced by the target speed. Moreover, optimal detection angles are obtained by numerical simulation, and these are very important for accurate and fast target detection, attack decision-making and developing multispectral detection platforms.

1. Introduction

Modern warfare demands higher operational requirements for battle space recognition, information acquisition and decision-making response. In a combat environment, target search and detection are the primary tasks of battlefield environmental cognition. At present, passive detection sensors in airborne photoelectric systems gradually highlight battlefield position and play important roles in concealing approach, silent attacks and situation assessments [1–5]. In current passive detection with a single spectral band, some parameters such as an aerial target's distance, speed, height, attitude and even detection angle can cause infrared radiation signals to become severe scintillation, presenting random characteristics. Especially in a complex interference environment, these infrared radiation signals are more easily submerged in a cluttered background, which complicates target detection, and even causes the airborne photoelectric system to lose the best chance to launch weapons [6–10].

With the development of infrared multispectral detection systems, infrared multispectral detection technology has been atopic of much current research. In contrast to single-band detection, multispectral detection offers stronger anti-interference capability and provides an extension in the spectral domain. Moreover, it can capture more detailed information corresponding to the desired target, realizing difference information complementarity and greatly improving the infrared target detection ability [7,11–14]. Target multispectral radiation characteristic analysis is an important aspect in the detection process; it mainly focuses on the infrared radiation spatial geometry distribution and spectral time-domain distribution that can determine the detection wavebands, angles and distance. To calculate a target multispectral radiation distribution, the temperature distribution of the target skin must be solved first. Lu and Wang analyzed the temperature distribution of the target skin by using the finite volume method (FVM); and combined with the reverse Monte Carlo method, they obtained infrared radiation characteristics of aircraft skin at high speed in the 8–14 μm waveband [15]. Based on a thermal analysis model, Mahulikar et al. obtained the temperature distribution of the target skin by numerical calculation and further studied the characteristics of long- and medium-wavelength radiation in low-speed flying conditions, determining how the skin transmission rate influences

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https://doi.org/10.1016/j.optlastec.2018.01.004
0030-3992/

multispectral radiation in the 3–5 µm and 8–14 µm wavebands [16]. Using the reverse Monte Carlo method, Pan *et al.* analyzed the spectral radiation intensity of aerial targets and obtained infrared radiation orientation characteristics at low and high speeds [17]. By using a numerical situation method, Kim et al. studied infrared radiation characteristics at short, medium and long wavelengths, respectively, and obtained target and background multispectral radiation curves over time [18].

Although all of above research efforts involve target multispectral radiation calculations, they lack sufficient analysis of target and environmental factors, ignoring the target attitude, height, tail flame radiation and reflected radiation such as solar, atmosphere and earth radiation that not only would change the spatial geometric distribution but also influence the optimal detection angles. For aerial targets, their complex structure, functional diversity and other factors such as aerodynamic heating, flight attitude and engine working status, would obviously alter the temperature distribution of the airborne nose, fuselage, wing and tail flame, resulting in a complex omnidirectional spectral radiation calculation.

The remainder of this paper is outlined as follows. In Section 2, we mainly calculate the temperature distribution of the target skin and tail flame. The results are analyzed thoroughly. In Section 3, to better present the spectral radiation characteristics of aerial targets, we utilize the envelope method to describe the multispectral radiation distribution. By considering the target height, detection angle, and the aerial target reflecting spectral radiation of the sun, atmosphere and earth, an omnidirectional spectral radiation envelope is built. In Section 4, we perform a simulation for the omnidirectional spectral radiation envelope to obtain the optimal detection angles by numerically. We conclude this paper in Section 5.

2. Temperature distribution of the aerial target

2.1. Temperature distribution of the target skin

The node network method is a very effective method for calculating the skin temperature field. The airborne body skin is divided into a finite quantity of consecutive surface elements whose center is a node. Convective heat transfer between nodes makes the whole-body skin form a thermal network diagram. By solving the thermal network balance equation, each node temperature of the body can be determined, and then the temperature distribution of the target skin can be obtained.

In Fig. 1, T_k is the temperature of the center of each node k, T_{k-1} and T_{k+1} are adjacent node temperatures, T_∞ is the air temperature, Q_{cv} is the convective heat between the body skin and the airflow, Q_r is the radiation heat of the body skin, Q_{out} is the external environment radiation heat absorbed by the target skin, Q_{con} is the convective heat between nodes and Q_{in} is the internal heat absorbed by the target skin.

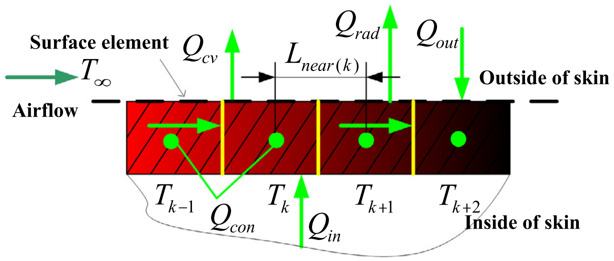

Fig. 1. Schematic diagram of convection heat transfer between nodes.

Therefore, the thermal balance equation for node k can be expressed as [19]

$$m_k c_k \frac{dT_k}{dt} = Q_{in} + Q_{con} + Q_{out} - Q_{cv} - Q_{rad}, \tag{1}$$

where m_k and c_k are the quality and specific heat capacity of the surface element, respectively. By considering the continuous temperature change between nodes as having little difference, the convective heat Q_{con} between adjacent nodes can be ignored, so that the thermal balance equation can be further written as

$$Q_{in} + Q_{out} - Q_{cv} - Q_{rad} = 0, \tag{2}$$

where $Q_{rad} = \varepsilon_k \sigma T_k^4 A_k$, ε_k is the skin emission rate, and A_k is the area of the surface element. The heat from the internal heat source is divided into two parts, heat radiation and heat conduction, so the node heat from the internal heat source by means of heat radiation is expressed by $Q_o = \eta_k \varepsilon_o \sigma T_o^4 A_o F_{o-k}$ and that by means of heat conduction is expressed by $Q_{o.con} = [\lambda_c (T_k - T_o) A_k]/L_o$, where T_o is the internal temperature, ε_o is the emission rate of the internal source, η_k is the absorption rate of node k, A_o is the area of the internal source, F_{o-k} is the radiation angle coefficient, λ_c is the heat conductivity coefficient and L_o is the distance of heat conductivity.

The internal heat source of the target only influences parts of the skin temperature while the aerodynamic heating gradually becomes the main factor influencing the skin temperature distribution with increasing target speed. Heat convection between the airflow and the skin is expressed by $Q_{cv} = h_x (T_k - T_{aw}) A_k$, where h_x is the heat transfer coefficient and T_{aw} is the steep temperature. The expressions for T_{aw} and h_x are as follows [20]:

$$\begin{cases} T_{aw} \approx T_\infty \left[1 + \frac{r_c (\gamma - 1) \mathrm{Ma}^2}{2} \right] \\ h_x = \frac{\lambda_a}{x} Nu_x = \frac{0.332 Re_x^{1/2} Pr^{1/3} \lambda_a}{x} \end{cases}, \tag{3}$$

where r_c is the recovery coefficient, γ is the mass heat capacity ratio, Ma is the target speed, λ_a is the air heat transfer coefficient, x is the characteristic length, Nu_x is the Nusselt number, Re_x is the Reynolds number, and Pr is the Prandtl number. The heat absorbed by the skin surface element from the external environment mainly comes from the solar, atmospheric and earth radiation, but when the target is at a high height, earth radiation attenuates strongly with distance. Consequently, the influence of earth heat radiation on the skin surface element can be ignored and the environmental radiation heat absorbed by skin node k can be written as

$$Q_{out} = Q_{sun} + Q_{air} = \eta_k E_{sun} \tau_h \cos\theta_s A_k + \eta_k \sigma T_\infty^4 A_k, \tag{4}$$

where E_{sun} is the solar irradiance, τ_h is the transmittance in the radiation distance from the outer atmosphere boundary to the target height, $\tau_h = \exp[-\overline{\mu(\lambda)} \cdot h]$, with $\overline{\mu(\lambda)}$ being the mean attenuation coefficient, and θ_s is the solar radiation angle, namely, the angle between the solar radiation light and the normal direction of the skin surface element. Therefore, formula (2) can be re-expressed as

$$\eta_k \varepsilon_o \sigma T_o^4 A_o F_{o-k} + \frac{\lambda_c}{L_o}(T_o - T_k) A_k + \eta_k E_{sun} \tau_h \cos\theta_s A_k$$
$$+ \eta_k \sigma T_\infty^4 A_k - h_x (T_k - T_{aw}) A_k - \varepsilon_k \sigma T_k^4 A_k = 0. \tag{5}$$

According to Kirchhoff's law, if the skin surface element is seen as a diffuse radiation gray body in the local heat balance and $\eta_k = \varepsilon_k$, then the formula (5) can be replaced by a heat flux density expression $q_{cv} = \varepsilon_k \sigma (T_\infty^4 - T_k^4) + q_{in} + q_{sun}$, where q_{cv}, q_{in}, and q_{sun}, respectively, are

$$\begin{cases} q_{cv} = h_x (T_k - T_{aw}) \\ q_{in} = \varepsilon_k \varepsilon_o \sigma T_o^4 \frac{A_o}{A_k} F_{o-k} + \frac{\lambda_c}{L_o} (T_k - T_o) \\ q_{sun} = \eta_k E_{sun} \tau_h \cos\theta_s \end{cases} \tag{6}$$