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Thermal characteristics of helicopters based on integrated fuselage structure/engine model

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ABSTRACT

Although the temperature distributions and infrared characteristics on the helicopter fuselage and in the exhaust plume have been great investigated in previous literatures, most of them are only in hover condition. In order to extend these models to any flight condition, a new integrated methodology is proposed considering the construction coupling and energy transfer relation of the helicopter. In this integrated methodology, we put forward a helicopter model to estimate the flight performance, including required power and attitude of the rotor, and a component-based model of the engine to evaluate the working performance of engines and exhaust plume parameters under various symmetrical steady level flight conditions. After this analysis of coupled working performance, the characteristics of flow and temperature fields are investigated through computational fluid dynamics. Subsequently, infrared radiation characteristics of helicopters are analyzed by a ray tracing method. This work can provide useful information for the energy management design and infrared radiation suppression of helicopters.

1. Introduction

The thermal characteristic of helicopter is an essential factor for helicopter performance, which has a crucial impact on the reliability and safety of systems' working and comfort of the passenger compartment [1–4]. Thus, it is of great importance to predict the thermal and infrared characteristics of helicopters. The intensity of infrared radiation (IR) is dependent on the temperature and surface structure of helicopters, as well as the hot exhaust plume. The main infrared sources include the following three parts: (a) engine hot parts or tailpipe, (b) exhaust plume, (c) airframe skin heated by the engine and plume.

Mahulikar et al. [4,5] studied the contribution of infrared radiation signatures of aerospace vehicles such as airplanes and helicopters. Because of a large amount of heat produced by engines, the tailpipes are the major and reliable source for the infrared signature level at the wavelength of 3–5 μm, which is larger than the infrared signature of the fuselage skin. Simultaneously, rear-fuselage skin is always heated by the exhaust plume from embedded engines. In a conclusion, the infrared signature of the aircraft is mainly in the rear of the aircraft. However, the visual area of the skin is many times larger than the area of tailpipes. Although the infrared signature of rear-fuselage is less than the tailpipe, it cannot be ignored to the total infrared signature level especially at the wavelength of 8–14 μm.

A lot of studies have covered the infrared radiation prediction model of the aerospace vehicles, concentrating on the infrared radiation of the skin, tailpipe, and exhaust plume. Lu et al. [6] presented a synthetic method for calculating the IR emitted from aircraft skin. Mahulikar et al. [7,8] considered the internal and external sources of infrared signature from surfaces of aircraft engine layout. Dix et al. [9] presented infrared signature data of a number of different convergent nozzle designs typical of those used in unmanned air vehicle applications. Rao et al. [10] analyzed two main sources (the powerplant and exhaust plume) of infrared signatures of aircrafts. Heragu et al. [11] developed a comprehensive scheme for the prediction of radiation from the engine exhaust and its incidence on an arbitrarily located sensor. Levy et al. [12] focused on the exhaust plume. Experimental investigation of infrared radiation from exhaust gases of a small turbojet engine was conducted. Kim et al. [13] proposed an infrared image synthesis method for the synthesis of the background and modeled infrared target. Pan et al. [14–16] investigated the effects of the engine exhaust system, rotor downwash and solar irradiance on the plume flow field, rear-fuselage temperature distribution and helicopter infrared signature. But their studies are only in the hover condition. Furthermore, the calculating parameters seem to be unrelated.

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Nomenclature

P_{xi}	profile-drag power (kW)
P_i	induced power (kW)
P_f	parasite drag power (kW)
P_M	power produced by engine (kW)
P_{tr}	power for driving the tail rotor (kW)
P_{acc}	power for pump and various attachments (kW)
P_R	power loss in transmission (kW)
C_T	thrust coefficient of the rotor
C_{y7}	lift coefficient of blade at 0.7 times the radius
C_{x7}	profile-drag coefficient of blade at 0.7 times the radius
T	thrust (N), $T \approx G$
ρ	density (kg/m^3)
R	radius of rotor (m)
Ω	angular velocity of the rotor (rad/s)
k_T	corrective coefficient of thrust
σ_r	solidity ratio
x	blade tip-root loss factor
k_p	corrective coefficient of profile drag power, $k_p = k_{p0} * (1 + 4.6 * \mu^2)$
$\overline{V}_0$	flight velocity of the helicopter, $\overline{V}_0 = \frac{V_0}{\Omega R}$
$\overline{v}_1$	induced velocity of rotor, $\overline{v}_1 = \frac{v_1}{\Omega R}$
$\sum C_x S$	parasite drag coefficient of the fuselage
μ	advance ratio, $\mu = \frac{V_0 \cos(-\alpha_E)}{\Omega R}$
λ_E	inflow ratio
α_E	equivalent attack angle of the rotor plane (°)
α_∞	lift-curve slope of blade element
φ_{7E}	collective pitch (°)
φ	incidence angle of rotor blade (°)
J	corrective coefficient of induced power
ζ	efficiency of mechanic transmission
$W_{a,cor}$	corrected mass flow of the compressor (kg/s)
T_{t4}	total temperature of the combustion chamber outlet (K)
π_{TH}	total pressure ratio of Gas turbine
P_c	power of the compressor (kW)
P_{AUX}	power for the attachments (kW)
P_{TH}	power of the gas turbine (kW)
W_4	flow rate at the outlet of the combustor (kg/s)
$W_{4,map}$	flow rate at the outlet on the characteristic curve of the combustor (kg/s)
W_5	flow rate at the outlet of the gas turbine (kg/s)
$W_{5,map}$	flow rate at the outlet on the characteristic curve of the gas turbine (kg/s)
P_{s9}	static pressure at the outlet of the exhaust nozzle (Pa)
P_H	ambient pressure (Pa)
α	excess air coefficient
$\vec{V}$	velocity vector (m/s)
p	static pressure (Pa)
$\bar{\bar{\tau}}$	stress tensor (Pa)
$\vec{g}$	acceleration of gravity (m/s^2)
$\vec{F}$	external body force (N)
E	total energy (J/kg)
k_{eff}	effective conductivity (W/(m·K))
T	temperature (K)
h_j	enthalpy for species j (J/kg)
$\vec{J}_j$	diffusion flux for species j (kg/(m^2·s))
S_h	source term (W/m^3)
Y_j	local mass fraction of species
I	radiance (W/(Sr·m^2))
$\vec{r}$	position vector (m)
$\vec{s}$	direction vector (m)
a	gas absorption coefficient (1/m)
σ	Stefan-Boltzmann constant (5.67 × 10^{-8} W/(m^2·K^4))
q_r	radiant heat flux (J)
λ	wavelength (μm)
$\varepsilon(\lambda)$	spectral emissivity of the object
c_1, c_2	radiance constant, $c_1 = 3.742 \times 10^{16}$ W · m^2 $c_2 = 1.4388 \times 10^2$ m · K
A_c	receiving area of detector, $A_c = 0.001$ m^2
A_m	surface element area of the object (m^2)
L	detection vector (m)
θ_m	zenith angle (°)
θ_c	angle between the viewing direction of the detector and L (°)
$\tau_{atm}(\lambda)$	spectral transmittance of the atmosphere
R_1, R_2	radiation heat transfer (J/m^2)
C_1, C_2	convection heat transfer (J/m^2)
K_{12}	conduction heat transfer (J/m^2)
A_S	area of the wall segment (m^2)

From the helicopter standpoint, with a turboshaft engine system, it is a nonlinear system, which is complex and coupled. In the past decades, integrated helicopter and engine control (IHEC) systems have made a rapid development. NASA Ames and Lewis Research Center initiated an IHEC program. This program was used in UH-60 helicopters as study vehicles, which can improve helicopter's agility and manipulate [17,18]. Sikorsky cooperating with other companies had implemented a variety of researches in IHEC. Achievements made in this program applied in the S-76 helicopter showed that the flying qualities had been greatly improved [19–22]. A new IHEC program with multi-stages was put forward by the US, where the Black Hawk helicopter was tested [23,24]. Britain and France also carried out some important IHEC programs [25].

Although this integrated method is approved that it can enhance the flight performance and reliability of helicopters, optimize and coordinate the various subsystems' work, this idea of integration is not yet applied to the thermal and infrared radiation prediction and analysis. Previous studies did many detailed studies on the infrared radiation of skin, tailpipe and exhaust plume individually, without modeling the whole helicopter. That is to say, they did not consider the coupled performance parameters of the rotorcraft between the rotor and engine according to the relationship of power transmission. As a matter of fact, the working performance of engines should match with the flight condition, as well as the parameters of the exhaust plume. Also, most of the previous literatures used the IR model only in hover condition. For this reason, when we focus on infrared radiation characteristic of the whole helicopter in the forward flight, all these performance parameters should be considered synthetically in the thermal and infrared radiation prediction.

The present paper aims at establishing a new analysis method for the thermal and infrared characteristic of helicopters in different flight conditions, considering the energy transfer relations of helicopters. This work can provide useful information for the working performance of engines, flight performance, energy management design and infrared radiation suppression of helicopters in the preliminary design and test.

2. Helicopter model

A helicopter model under design is shown in Fig. 1. This type of helicopter is composed of the fuselage, engine, engine cabin, exhaust system, rotor plane, horizontal-tail and vertical-tail. The coordinate system is fixed at the center of the rotor plane.