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Numerical simulation of the aerodynamic influence of an aircraft on the hose-refueling system during aerial refueling operations ☆

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ABSTRACT

The aerodynamic characteristics of the flow field of an embarked buddy-refueling aircraft are analyzed to technically aid the docking between the embarked buddy-refueling aircraft and the receiver. A three-surface geometric model of the embarked buddy-refueling aircraft is designed with CATIA software, and then the model is imported into Fluent Module of Workbench Software to generate an unstructured tetrahedral mesh. Based on CFD technique, the turbulence model adopts the standard k–ε equations and the control theory adopts three-dimensional N–S equations. The aerodynamic characteristics of the flow field of the embarked buddy-refueling aircraft are numerically simulated with energy conservation equations and the basic characteristics of the flow field such as the pressure, velocity, trapped vortex and the temperature of jet blast are derived through the simulation. The results indicate the efficiency of the simulation method to analyze the aerodynamic characteristics of the flow field of the embarked buddy-refueling aircraft and the consistency with the experimental results.

The embarked buddy-refueling aircraft is a multi-role military aircraft which can refuel other inflight fighters of the same type. It has a long history of decades along with the development of carriers and embarked aircrafts. The embarked buddy-refueling aircraft KA-6D, as an adaption of A-6A and A-6E has been in service from 1966 to early 21th century. The inflight endurance of the aircraft has been strengthened and the operational radius has been enlarged based on various combat experiences, and the aircraft contributes a lot to the achievements of the carrier air wings. The embarked buddy-refueling aircraft of the US Navy in active service is F/A-18E/F with a refueling pod of RDC-1 which enables inflight buddy-refueling missions. The development history and operation experience of the US Navy's embarked buddy-refueling aircraft deserve thorough studies of the aircraft research and development department and equipment users of China.

Researchers both at home and aboard have made efforts to study inflight refueling technique. A simulation platform for automated refueling for UAVs to which the computer vision technology is applied is designed and built based on the hose-drogue refueling system in reference [1]. In reference [2], the Kane method is applied to build a system model and analyze the dynamic response of the system based on boom refueling equipment. A dynamic model of docking between drogue and probe is studied based on multi-body system dynamics in reference [3]. In reference [4], the author summarizes the inflight refueling technique of boom and drogue-probe systems, and worldwide achievements on system modeling and control technique about inflight refueling technique in recent years are also introduced. The turbulence performance of fixed and retractable probes in flight is analyzed in reference [5]. Outcomes on modeling and control theory in docking phase for hose-refueling are summarized in reference [6]. Boom refueling technique is discussed in reference [7], where a mathematical model of retractable spear for boom refueling which is a multi-input multi-output, coupling and nonlinear system is built. In reference [8], the model of the relative position relation for tanker and UAVs is built and analyzed with the vision pictures of the camera. The flow field characteristics of inflight refueling are analyzed in reference [9]. The flow field of refueling is illustrated literally and the experimental data of the docking phase during refueling are presented without any theoretical basis or simulation analysis. In reference [10], a dynamic model for hose-drogue system as multistage pendulum-connected rigid links of a changeable length is presented based on lumped parameter method. In order to study the hose whipping phenomenon, a dynamic model for hose-drogue combination where the changeability of elasticity and length of the system are taken into account is presented in

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reference [11] based on multi-rigid-body dynamics of lumped parameters. The issues on flight dynamic and control are discussed in reference [12]. An aerial refueling system model of hose-drogue is built and simulated in reference [13]. An aerial refueling system of controlled drogue is studied in reference [14]. In reference [15], the influence of the wind and flight data on the aerial refueling operation is discussed. The impact of variation in mass of the refueled aircraft on the aerial refueling operation is studied in reference [16]. The auto-refueling technology with sensors during flight is introduced in reference [17]. The automation of the position of the drogue is studied in reference [18]. The relative position based on vision estimation is discussed in reference [19] and a vision sensor for aerial refueling is introduced in reference [20]. Although several respects in the domain have been over-studied by researchers at home and aboard, certain problems are still overlooked. Although the issue has been over-studied in several respects, such as the modeling of multi-body system dynamics and the visual simulation, certain problems such as the influence of intake and exhaust of the engine on the aerodynamic performance of the hose-drogue system are still overlooked; the aerodynamic interactions of the buddy-refueling aircrafts of the same type have not been studied yet. No public academic reports on inflight refueling of embarked buddy-refueling aircrafts have been obtained, and there is a lack of in-depth research on the impact of the flow field of tanker on the hose-drogue system based on CFD technology.

The issue of dynamic flow field of three-surface embarked buddy-refueling aircraft at high altitude is discussed based on CFD technique. Furthermore, the influence of engine intake and the exhaust on the flow field is taken into account, and the aerodynamic characteristics of the flow field of hose-drogue refueling equipment are also analyzed. It is expected that the research of the paper can technically support the inflight refueling technique.

1. Governing equations

In the numerical simulation of aerodynamic characteristics of embarked buddy-refueling aircraft based on CFD theory, the turbulence model of airflow field applies the standard k–ε equations; the control theory of fluid mechanics applies three-dimensional N–S equations, and heat exchange system applies the conservation of energy equations.

The standard k–ε equations of airflow field turbulence model are as follows [21–23]:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{1}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \tag{2}$$

And the three-dimensional N–S equations of control theory [24]:

$$\frac{\partial \rho u}{\partial t}+\operatorname{div}(\rho u\boldsymbol{u})=\operatorname{div}(\mu\operatorname{grad}u)-\frac{\partial p}{\partial x}+S_u \tag{3}$$

$$\frac{\partial \rho v}{\partial t}+\operatorname{div}(\rho v\boldsymbol{u})=\operatorname{div}(\mu\operatorname{grad}v)-\frac{\partial p}{\partial y}+S_v \tag{4}$$

$$\frac{\partial \rho w}{\partial t}+\operatorname{div}(\rho w\boldsymbol{u})=\operatorname{div}(\mu\operatorname{grad}w)-\frac{\partial p}{\partial z}+S_w \tag{5}$$

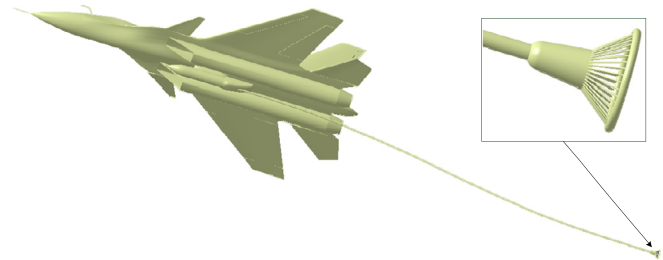

Fig. 1. Geometric model of embarked buddy-refueling aircraft.

A system with heat exchange flow should meet conservation of energy equations as follows:

$$\frac{\partial(\rho T)}{\partial t}+\operatorname{div}(\rho\boldsymbol{u}T)=\operatorname{div}\left(\frac{k_r}{c_p}\operatorname{grad}T\right)+S_T \tag{6}$$

where ρ is the fluid density, k is turbulence energy, t is time, u_i is the time average velocity, μ is kinematic viscosity of the fluid, μ_t is dynamic viscosity, σ_k is Prandtl constant with turbulence energy k, G_k is the production of turbulence energy k caused by average velocity gradient, G_b is the produce of turbulence energy k originated from buoyancy, ε is dissipation rating of turbulence energy, Y_M is the contribution of pulsing dilatation in turbulence, S_k is the source item defined by the user, σ_ε is the Prandtl constant with dissipation rating ε, $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are empirical constants, S_ε is the source term defined by the user, $\boldsymbol{u}$ is velocity vector, u, v and w are components of $\boldsymbol{u}$ on x, y and z-axis, p is pressure on fluid microelement, div( ) is the divergence, grad( ) is the gradient, S_u is the generalized source term of conservation of momentum equations on direction u, S_v is the generalized source term of conservation of momentum equations on direction v, S_w is the generalized source term of conservation of momentum equations on direction w. T is Kelvin's temperature (K); k_r is heat transfer coefficient, c_p is specific heat, S_T is viscous dissipation item [25].

The temperature unit conversion equation is as follows:

$$T=t+273.15 \tag{7}$$

where t is Centigrade temperature, °C.

In the combustion module of Fluent, the chemical equation for aviation fuel combusting with air to produce exhaust gases is as follows [16]:

$$2C_{19}H_{30}+53O_2=38CO_2+30H_2O \tag{8}$$

where $C_{19}H_{30}$ is the aviation fuel; O_2 is oxygen; CO_2 is carbon dioxide; H_2O is water vapor.

2. Building of geometric model

A possible variant of Su-33 as an embarked buddy-refueling aircraft is conceptually designed referring to Russia's embarked aircraft Su-33 with CATIA software in modeling stage (see Fig. 1). The embarked buddy-refueling aircraft is a single-seat, twin-engine, three-surface configuration military aircraft of a pluralistic type. It is a normal multi-role fighter that can be used as an embarked buddy-refueling aircraft after the generalized refueling pod is mounted when needed.

The main dimensions of the aircraft are as follows. Length: 21.18 m, height: 5.72 m, wingspan: 14.7 m, hose-drogue type, refueling pod type UPAZ, length of hose: 26 m and fuel filling speed: 2300 L/min.

The aircraft is a rigid body which can keep the geometric shape during refueling; the hose-drogue system is assumed as a flexible structure which can remain steady temporarily during refueling.