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Modeling and simulation of a time-varying inertia aircraft in aerial refueling

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Abstract Studied in this paper is dynamic modeling and simulation application of the receiver aircraft with the time-varying mass and inertia property in an integrated simulation environment which includes two other significant factors, i.e., a hose–drogue assembly dynamic model with the variable-length property and the wind effect due to the tanker's trailing vortices. By extending equations of motion of a fixed weight aircraft derived by Lewis et al., a new set of equations of motion for a receiver in aerial refueling is derived. The equations include the time-varying mass and inertia property due to fuel transfer and the fuel consumption by engines, and the fuel tanks have a rectangle shape rather than a mass point. They are derived in terms of the translational and rotational position and velocity of the receiver with respect to an inertial reference frame. A linear quadratic regulator (LQR) controller is designed based on a group of linearized equations under the initial receiver mass condition. The equations of motion of the receiver with a LQR controller are implemented in the integrated simulation environment for autonomous approaching and station-keeping of the receiver in simulations.

1. Introduction

Air to air refueling is an effective method of increasing the endurance and range of aircraft. Most recently, there has been increasing interest in autonomous aerial refueling (AAR) for the continuing research into unmanned aerial systems. Over the last decade, there have been a wealth of research and academic publications on the theoretical and practical aspects of automating the refueling process covering aircraft control, sensor systems, and their integration.[1–4] In order to further develop and evaluate these researches, it is critical to model the whole aerial refueling system with sufficient accuracy, taking into account all major factors including the aircraft, aerodynamic and atmospheric disturbances, and refueling apparatus. For the probe-drogue refueling, three of the most significant factors are the dynamic model of the receiver aircraft with the time-varying mass and inertia property, a hose–drogue assembly (HDA) dynamic model with the variable-length property and the wind effect due to the tanker's trailing vortices.

It is generally accepted that it is sufficient to consider the dynamics of an aircraft at a number of fixed, specified, overall

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weights.[5] If a mass change is within about 5% of the beginning mass after a period of 60 s, the constant mass assumption is considered acceptable.[6] Therefore, the research community has put little effort into the investigation of dynamics of systems with inertia variation. However, the mass change of the receiver is up to 18.8% within a period of 60 s in aerial refueling. Under this condition, the effect of the mass change on the dynamics of the aircraft could not be negligible. Earlier aerial refueling studies[7,8] either ignore the effect of mass transfer completely or treat it as a disturbance causing parametric uncertainty. To develop an accurate dynamic model of the aircraft, Dogan et al.[9–11] proposed a set of nonlinear, 6-DOF equations of motion of a receiver aircraft undergoing aerial refueling. The equations, including the time-varying inertia associated with fuel transfer as well as the vortex-induced wind effect from the tanker, are expressed relative to the tanker and very rigorous from the mathematical perspective. Even so, they have a very complex mathematical expression and seem too complicated to be easily applied to the simulation and analysis.

This paper focuses on the development of the derivation of a simpler aircraft model with the time-varying mass and inertia property. By extending equations of motion of a fixed weight aircraft,[5] comparing with the ones developed by Dogan et al., the equations can reflect the time-varying mass and inertia property of an aircraft more factually due to (A) reflecting both the fuel increase and the fuel decrease at the same time (i.e., the fuel transfer in refueling and the fuel consumption by engines), and (B) the fuel tanks having a rectangle shape rather than a mass point, (C) the equations of motion are derived relative to an inertial frame rather than the tanker body frame, (D) the model has a simpler mathematical expression and is easily applied to the simulation and analysis. Thus, they have a more strong universality.

To validate the proposed aircraft model in an integrated simulation environment for probe-drogue-based autonomous aerial refueling, a dynamic model of the HDA developed by the authors[12–16] and a dynamic model of the vortex effect in aerial refueling developed by Dogan et al.[17–19] are also used in the simulation.

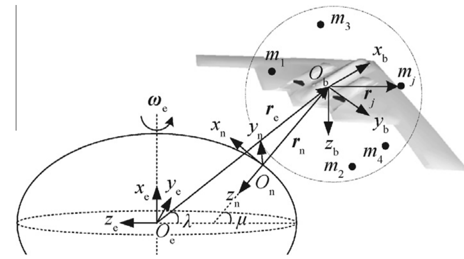

Fig. 1 Coordinate frames for modeling.

and $\boldsymbol{\omega}_{\mathrm{e}}$ is the absolute angular velocity vector of Earth' rotation, $\boldsymbol{r}_{\mathrm{n}}$ is the position vector of the center of mass of the aircraft in $O_{\mathrm{n}}x_{\mathrm{n}}y_{\mathrm{n}}z_{\mathrm{n}}$.

To facilitate the derivation of the dynamics equations including the effect of time-varying inertia, an aircraft-fuel system is considered to comprise two parts as (A) solid, (B) fuel in tanks[11] as shown in Fig.1. The total amount of mass that occupies the fuel pipes has not been included here. The solid part is considered rigid with constant mass. The origin of $O_{\mathrm{b}}x_{\mathrm{b}}y_{\mathrm{b}}z_{\mathrm{b}}$ is chosen to be at the center of mass of the solid part, such that the standard definitions of aerodynamic variables and aerodynamic stability derivatives can be directly used without any modification or reinterpretation.[5] The fuel in fuel tanks is represented by k masses. The mass of fuel in the jth fuel tank, $m_j (j = 1, 2, \ldots, k)$, is time varying. The position vector from the center of mass of the fuel to the origin of $O_{\mathrm{b}}x_{\mathrm{b}}y_{\mathrm{b}}z_{\mathrm{b}}$, $\boldsymbol{r}_j$, is assumed to be a constant.

2.1.2. Translation kinematics

Taking a derivative of the inertial position vector $\boldsymbol{r}_{\mathrm{e}}$ of the center of mass of the receiver aircraft in $O_{\mathrm{e}}x_{\mathrm{e}}y_{\mathrm{e}}z_{\mathrm{e}}$ yields[5]

$$\dot{\boldsymbol{r}}_{\mathrm{e}} = \boldsymbol{B}^{\mathrm{T}}\boldsymbol{V}_{\mathrm{b}}^{\mathrm{e}} = \boldsymbol{B}^{\mathrm{T}}\boldsymbol{V}_{\mathrm{b}} + \boldsymbol{\omega}_{\mathrm{e}} \times \boldsymbol{r}_{\mathrm{e}} \tag{1}$$

$$\boldsymbol{B} = \boldsymbol{B}_{\mathrm{B}}\boldsymbol{B}_{\mathrm{G}} \tag{2}$$

$$\boldsymbol{B}_{\mathrm{B}} = \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & \sin\phi\cos\theta \\ \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi & \cos\phi\cos\theta \end{bmatrix} \tag{3}$$

2. Equations of motion of a time-varying inertia aircraft

2.1. Equations of motion relative to Earth-centered inertial frame

2.1.1. Definitions of coordinate frames and assumptions

A receiver aircraft often performs long-range, even globe-straddling military operations. Under this condition, the effect of the shape and the rotation of the Earth on the dynamics of the receiver aircraft should not be totally omitted. Therefore, without any loss of generality, an Earth-centered inertial (ECI) frame is chosen as an inertial reference frame. Fig. 1 shows the ECI frame ($O_{\mathrm{e}}x_{\mathrm{e}}y_{\mathrm{e}}z_{\mathrm{e}}$), an aircraft-body coordinate (ABC) frame ($O_{\mathrm{b}}x_{\mathrm{b}}y_{\mathrm{b}}z_{\mathrm{b}}$), and an intermediate north-east-down (NED) frame ($O_{\mathrm{n}}x_{\mathrm{n}}y_{\mathrm{n}}z_{\mathrm{n}}$) on the surface of the Earth,[5]

$$\boldsymbol{B}_{\mathrm{G}} = \begin{bmatrix} \cos\mu & -\sin\mu\sin l & \sin\mu\cos l \\ 0 & \cos l & \sin l \\ -\sin\mu & -\cos\mu\sin l & \cos\mu\cos l \end{bmatrix} \tag{4}$$

where $\boldsymbol{\omega}_{\mathrm{e}} \times \boldsymbol{r}_{\mathrm{e}}$ denotes the absolute velocity of surrounding air at $\boldsymbol{r}_{\mathrm{e}}$, $\boldsymbol{B}$ the rotation matrix from $O_{\mathrm{e}}x_{\mathrm{e}}y_{\mathrm{e}}z_{\mathrm{e}}$ to $O_{\mathrm{b}}x_{\mathrm{b}}y_{\mathrm{b}}z_{\mathrm{b}}$, $\boldsymbol{B}_{\mathrm{B}}$ the rotation matrix from $O_{\mathrm{n}}x_{\mathrm{n}}y_{\mathrm{n}}z_{\mathrm{n}}$ to $O_{\mathrm{b}}x_{\mathrm{b}}y_{\mathrm{b}}z_{\mathrm{b}}$, $\boldsymbol{V}_{\mathrm{b}}^{\mathrm{e}}$ the absolute velocity vector of the aircraft center of mass expressed in $O_{\mathrm{b}}x_{\mathrm{b}}y_{\mathrm{b}}z_{\mathrm{b}}$ relative to $O_{\mathrm{e}}x_{\mathrm{e}}y_{\mathrm{e}}z_{\mathrm{e}}$, $\boldsymbol{V}_{\mathrm{b}}$ the relative velocity vector of the aircraft center of mass expressed in $O_{\mathrm{b}}x_{\mathrm{b}}y_{\mathrm{b}}z_{\mathrm{b}}$ relative to $O_{\mathrm{e}}x_{\mathrm{e}}y_{\mathrm{e}}z_{\mathrm{e}}$. ϕ, θ, ψ are the orientation angles. l, μ are the longitude and latitude.

From Eq. (1), the translational kinematic equation of the aircraft relative to $O_{\mathrm{e}}x_{\mathrm{e}}y_{\mathrm{e}}z_{\mathrm{e}}$ could be expressed as

$$\boldsymbol{V}_{\mathrm{b}}^{\mathrm{e}} = \boldsymbol{V}_{\mathrm{b}} + \boldsymbol{B}(\boldsymbol{\omega}_{\mathrm{e}} \times \boldsymbol{r}_{\mathrm{e}}) \tag{5}$$