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Modeling and simulation of bow wave effect in probe and drogue aerial refueling

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Abstract In a probe and drogue aerial refueling system, the bow wave of the receiver aircraft will produce a strong aerodynamic effect on the drogue once the receiver follows the drogue at a close distance. It is a major difficulty of docking control in the probe and drogue refueling. This paper analyses the bow wave effect and presents a simple method to model it. Firstly, the inviscid flow around the receiver is modeled based on the stream function defined by basic stream singularities. Secondly, a correction function is developed to eliminate the error caused by the absence of air viscosity. Then, the aerodynamic coefficients are used to calculate the induced aerodynamic force on the drogue. The obtained model is in an analytical form that can be easily applied to the controller design and the real-time simulations. In the verification part, computational fluid dynamics (CFD) simulation tests are conducted to validate the obtained flow fields and aerodynamic forces. Finally, the modeling method is applied to an F-16 receiver aircraft in a previously developed autonomous aerial refueling simulation system. The simulations results are analyzed and compared with the NASA flight-test data, which demonstrates the effectiveness of the proposed method.

1. Introduction

Aerial refueling has demonstrated great benefits to aviation by increasing an aircraft's effectiveness through extending its range and endurance.[1] Recently, the development of unmanned aerial vehicles (UAVs) has pioneered a new realm for the application of aerial refueling and the developments of autonomous aerial refueling (AAR) techniques for UAVs make new missions and capabilities possible, like the ability to remain on station for days or even weeks.[2]

Currently, there are two major types of aerial refueling in operation: probe-drogue refueling (PDR) and boom-receptacle refueling (BRR),[3] and both of them play important roles in modern civil and military applications. PDR systems are considered simpler and more flexible than BRR systems, because PDR systems can be adapted to various refueling speeds and multiple receiver aircraft.[4] However, the significant drawback of PDR is that the drogue is completely passive and susceptible to the aerodynamic influence from multiple aspects, including the wind effect from the tanker, the receiver and the atmospheric disturbance.[5,6]

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The wind effect from the receiver aircraft is generally referred to as the forebody effect[2] or the bow wave effect[7]. As shown in Fig. 1, a strong bow wave induced by the forebody of the receiver will change the flow field that the drogue is exposed to, and the forebody flow field tends to push the drogue away when they are close to each other (within few meters). Since the drogue is more flexible than the receiver, precise control is a tough task. In manned refueling procedures, experienced pilots can accomplish the refueling mission by carefully anticipating the movement of the drogue. However, it is still difficult for unmanned aerial refueling. NASA performed the first unmanned aerial refueling test in 2006, where only two out of six capture attempts succeed due to "the drogue is pushed upward by the forebody flow field of the receiver"[2] and they named it the "forebody effect".[2]

So far, the wind effects from the tanker and atmospheric disturbance have already been well studied as presented in Ref.[8], but the bow wave effect has yet received very little attention. NASA performed flight tests to find ways to estimate the range of the bow wave effect in Ref.[9]. In recent years, numerical models[10,11] were developed based on the look-up tables obtained by computational fluid dynamics (CFD) simulations. In 2014, a CFD-simulation analysis was carried out by Khan and Masud[12] to find the optimal initial location of the refueling basket such that the forebody flow field has minimal aerodynamic effects on the drogue. However, the procedures to obtain data by CFD simulations are very complex and highly time-consuming. Moreover, the numerical models are inconvenient for the controller design. In Ref.[13], an analytical model based on the stream function was developed for BRR, but the model is only available to the specific aircraft and it is not suitable for PDR.

In this paper, a method to model the bow wave effect in PDR is developed. Firstly, the inviscid flow around the receiver is modeled based on the stream function defined by basic stream singularities. Secondly, a correction function is developed to eliminate the error caused by the absence of air viscosity. Then, the aerodynamic coefficients are used to calculate the induced aerodynamic force on the drogue. Finally, the obtained aerodynamic force is incorporated into a hose-drogue dynamic model to simulate the drogue movement under the bow wave effect. The contributions of this paper are as follows: (1) a simple and analytical model of the bow wave effect for PDR is proposed for the first time, which is easily applied to the controller design and the real-time simulations; (2) the proposed method is flexible, which is applicable to difference refueling conditions, such as different altitudes, speeds, or different types of drogues.

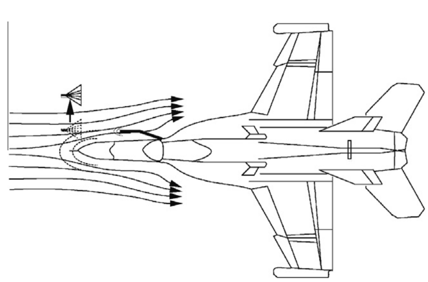

Fig. 1 Illustration of F/A-18B bow wave effect during final contact state.

The paper is organized as follows. Section 2 gives a comprehensive mathematical analysis of the bow wave effect. Section 3 describes the procedures to obtain the forebody flow field of the receiver. Section 4 introduces the method to obtain the aerodynamic force of the drogue under the effect of the induced flow field. To validate the proposed method, comparisons with the results from the CFD simulation and the NASA flight test are made in Section 5, which indicates that the modeling method is effective and practical. Finally, Section 6 presents the conclusions and future work.

2. Problem formulation

2.1. Frames and notations

The overview diagram of the PDR system is presented in Fig. 2. There are two major frames used in this paper: the tanker wind reference frame T_W $(O_{T_W}x_{T_W}y_{T_W}z_{T_W})$ and the receiver nose frame R_N $(O_{R_N}x_{R_N}y_{R_N}z_{R_N})$, where O_{T_W} is the origin of frame T_W which is fixed to the conjunctive point between the tanker body and the hose, and the direction of $O_{T_W}x_{T_W}$ is aligned with the wind frame of the tanker which is also parallel to the free stream velocity V_∞ (V_∞ is equal and opposite to the tanker airspeed V_T). The origin of R_N is fixed to the tip of the receiver nose, and the axes of R_N are aligned with T_W. The ground inertial frame I $(O_I x_I y_I z_I)$ is a north-east-down (NED) system and R_B $(O_{R_B}x_{R_B}y_{R_B}z_{R_B})$ is defined as the body frame of the receiver aircraft whose origin is at the center of the aircraft and axes aligned with aircraft reference directions (nose-right-down).[14] The drogue body frame $D_B(Oxyz)$ is defined the same way as R_B, whose origin is located at the center of the drogue and axes are aligned with the symmetric axes of the drogue (see Fig. 2). $\boldsymbol{p}_{dr}$ and $\boldsymbol{p}_{pr}$ are relative positions of drogue and probe.

Rules of defining notations for the frame description and transformation are made in this paper:

A right superscript on a vector will specify the frame that the vector is defined.

The rotation matrix from frame B to frame A will be denoted by $\boldsymbol{R}_{A/B}$. For example, $\boldsymbol{p}_{dr}^{R_N}$ denotes the position of drogue $\boldsymbol{p}_{dr}$ defined in the frame R_N, and $\boldsymbol{R}_{T_W/R_N}$ denotes the rotation matrix from R_N to frame T_W.

Two assumptions can be made for the simplification of the bow wave effect model:

Assumption 1. α_R, β_R are small, and let $\alpha_R = 0^\circ$, $\beta_R = 0^\circ$.

Assumption 2. $\boldsymbol{R}_{T_W/D_B} = \boldsymbol{R}_{T_W/R_N} = \boldsymbol{R}_{T_W/R_B} = \boldsymbol{I}_3$.

Remark 1. Considering that the angle of attack of the receiver α_R is generally small ($0^\circ < \alpha_R < 10^\circ$) during the capture stage, and only a small region around the forebody of the receiver aircraft (with length about 2 m from the tip) is concerned, the existence of α_R will have insignificant effect on the calculation of the induced velocity field. So, it is reasonable to assume that the angle of attack of the receiver $\alpha_R = 0^\circ$. For the same reason, the angle of sideslip of the receiver β_R is assumed to be zero. Under Assumption 1, the body frame and wind frame of the receiver will have the same direction, and then the complex steps for coordinate transformations can be omitted.